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UC-70 — Waste Disposal and Processing

SAFETY ANALYSIS OF WASTE DISPOSAL BY HYDRAULIC FRACTURING AT OAK RIDGE

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OAK RIDGE NATIONAL LABORATORY
operated by
UNION CARBIDE CORPORATION
for the
U.S. ATOMIC ENERGY COMMISSION

#54

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ABSTRACT

The concept of hydraulic fracturing as a method for the permanent disposal of radioactive waste solution is founded upon methods developed by the petroleum industry. The basic procedure is to generate a horizontal fracture in the impermeable shale which is located several hundred feet underground. This is done by pumping water at high pressure down into a cased well and out into the shale through slots cut in the well casing. A mixture of waste solution, portland cement, and clay is then pumped into the fracture, the well closed in, and the cement mixture allowed to set up, forming a solid sheet of hardened grout which becomes essentially part of the host rock.

This report describes the facilities which have been designed and constructed at ORNL for this purpose, together with information concerning ORNL experience with 14 injections performed between February 1964 and September 1970. The safety analysis contained herein leads to the conclusion that, within the operating limits specified, hydrofracture disposal of radioactive waste can be carried out in a safe and orderly manner with no significant present or future hazard to the public or to the environment.

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INTRODUCTION

The concept of hydraulic fracturing as a method for the permanent disposal of radioactive waste solutions arose from the experience of the petroleum service companies. This experience, largely of an empirical nature, has been concerned with the creation of large fractures in permeable rock. These fractures can be either horizontal or vertical, and there is much dispute among geologists as to which fracture orientation will be formed in a given set of conditions. For safe disposal of radioactive waste it is imperative that the fracture formed be horizontal; for this reason a determination of the fracture orientation at the Oak Ridge site was the necessary first step in proving hydraulic fracturing to be a potentially useful method for waste disposal.

Three fracturing experiments were conducted to determine the fracture orientation in the Conasauga shale beds at Oak Ridge. In these experiments a cement grout was tagged with a radioactive tracer and pumped down an injection well that had been previously slotted at the desired depth. After the injection was completed the formations were cored, and the horizontal or nearly horizontal nature of the fractures was verified. Details of these experiments are given in ORNL-4259.

Considerable mix development work was required to determine the significant variables affecting the properties of the waste-cement grouts and how to adjust these variables to obtain a grout of the desired properties. Desirable grout properties included the following:

1. a viscosity of less than 20 P,
2. a pumping time of at least 8 hr,
3. a setting time of less than 1 day,
4. a compressive strength of greater than 100 psi,
5. no phase separation (separation of free water on standing),
6. good radionuclide retention, and
7. low cost.

These properties were achieved with a dry solids blend that contains portland cement, fly ash to extend the cement and bind the strontium, attapulgite clay to suspend the cement and reduce phase separation, Grundite clay to bind the cesium, and a sugar to retard the setting time. The relative proportions of these various ingredients can be varied within limits to adjust for variations in the waste concentration or cement properties. A detailed account of the waste development program is given in ORNL-4259.

Beginning in 1959, when the first of seven field-scale fracturing experiments was undertaken, and continuing on through to the latest injection of intermediate level wastes (ILW)* on September 23, 1970, ORNL's efforts to prove that hydraulic fracturing is a potentially useful method for radioactive waste disposal have been singularly successful. These efforts, largely funded by the AEC's Division of Reactor Development and Technology, were initiated in the late fifties and have since been led by the Health Physics Division's Radioactive Waste Disposal Section, with valuable assistance from the Chemical Technology, Plant and Equipment, and General Engineering Divisions. Current fracturing disposal operations are primarily the responsibility of the Laboratory's Operations Division. Since December of 1966, disposal by hydraulic fracturing has been a routine operating procedure, enabling the Laboratory to permanently dispose of over 600,000 gal of ILW waste containing almost 400,000 Ci of mixed fission products and over 80 g of ^{239}Pu without releasing significant amounts of contamination to the Laboratory environment.

In 1970 the AEC requested that ORNL stop the routine disposal of wastes by hydrofracturing until a new safety analysis was completed. The impetus was the "AEC Immediate Action Directive,"[1] which required that solid wastes containing known or detectable amounts of transuranium isotopes be retained in a retrievable form. Later, statements of AEC policy indicated that (1) wastes containing significant amounts

*ORNL's intermediate-level liquid waste is an alkaline evaporator-concentrate normally containing less than 1 Ci/gal of beta and gamma activity and less than 1.0×10^{-4} Ci/gal of alpha activity.

1. R. E. Hollingsworth, General Manager, U.S. Atomic Energy Commission, *Policy Statement Regarding Solid Waste Burial*, IAD No. 0511-21, Mar. 20, 1970.

of beta-gamma nuclides[2] were not necessarily included in the directive and (2) that it was desirable to dispose of wastes permanently "on site" if suitable methods were available.[3] This report is aimed at providing the required safety analysis (1) to decide that hydraulic fracturing is suitable and safe for disposal of current ORNL ILW waste and (2) to suggest modifications for upgrading the hydraulic fracturing plant to handle ORNL ILW waste for the next five or more years.

A subsequent report will (1) present a detailed plan for the disposal of all wastes by hydraulic fracturing, (2) present a conceptual design for converting the hydraulic fracturing facility to a permanent facility capable of handling wastes containing higher levels of ^{90}Sr and transuranium nuclides, and (3) present alternative methods for disposal of waste by shipping solid residues to the national repository.

Ultimately, all ORNL programs that generate radioactive waste will be affected if hydraulic fracturing is abandoned.[4] This disposal method, or some suitable alternative, is not only needed for the disposal of ILW waste, but for other wastes as well (e.g., residues resulting from the treatment of low-level waste water, sludges in the bottoms of 27-year-old concrete tanks in the Tank Farm, high-activity wastes from the Californium Program at TRU, and the high-activity wastes from fuel reprocessing programs). At present, residues from the Waste Water Treatment Plant are discharged into surface trenches which lie open to the weather and above zones of circulating groundwater. Although the trenches have contained the radioactive strontium and cesium adequately, a more effective means for permanent disposal of these residues is needed.

The 315,000 gal of sludges currently held in the Tank Farm, containing approximately 500,000 Ci of ^{90}Sr. and about 5 kg of ^{239}Pu, could be slurried, pumped to the hydraulic fracturing facility, and hydrofractured as a grout into the Conasauga shale at concentrations not greatly higher than in past levels of injection. The relatively small volumes of high-level waste produced at TRU and in fuel reprocessing pilot plants could be stored until radioactive decay would allow it to be incorporated into ILW waste for disposal by hydrofracturing.

It is a matter of considerable importance to the Laboratory, then, (1) to reassess the long-term safety of this method of disposal and (2) to examine the existing facility for needed improvement that would bring it up to the engineering standards of other such facilities at the Laboratory, recognizing that it was built originally as an experimental facility with only light shielding, with no double containment, and with only minimal off-gas capacity.

DESCRIPTION OF MELTON VALLEY SITE

Location

The main operating area of the Oak Ridge National Laboratory is located in Bethel Valley some six to eight miles southwest of the city of Oak Ridge and in the south central part of the Oak Ridge AEC reservation. Certain of the Laboratory's operations, including the Hydraulic Fracturing Plant for Waste Disposal, are located in Melton Valley, about a mile to the southeast of the main area. Melton Valley is drained to the southwest by Melton Creek, which flows into the small impoundment of White Oak Lake and thence into the Clinch River. Melton Creek and White Oak Lake are both continuously monitored for radioactive contaminants. The hydraulic fracturing plant is a half mile or more from the nearest major facility and is adjacent to one of the burial grounds for solid radioactive waste (Burial Ground No. 5) as shown in Fig. 1.

Geology

Oak Ridge is located in the "Valley and Ridge" physiographic province, a belt of faulted and folded rock which lies between the "Blue Ridge" subdivision of the Appalachian Plateau to the southeast and the Cumberland Plateau to the northwest. In the Oak Ridge area the province is about 50 miles wide and is marked by a series of great overthrust faults, in each of which a layer of rock very roughly two miles thick has moved as much as several tens of miles to the northwest, overriding the similar sheet of rock in front of it and in turn overridden by the sheet behind it.

The two fault sheets of immediate interest to the work at Oak Ridge are composed of four formations. The oldest is the Rome sandstone, of lower Cambrian age. That part of the upper Rome present in the hydraulic fracturing plant area is largely composed of beds of hard brittle quartzite 1 in. to 1 ft thick. The

2. H. A. Nowak, Director, Division of Waste and Scrap Management, U.S. Atomic Energy Commission, *Draft of AEC Manual Chapter 0511 – Radioactive Waste Management*, Mar. 30, 1971.

3. G. T. Seaborg, Chairman, U.S. Atomic Energy Commission, letter (not dated) to J. Skubitz, U.S. House of Representatives, Submitted for the Record at the FY 1972 Authorization Hearings before the Joint Congressional Committee on Atomic Energy, Mar. 16, 1971.

4. Letter, F. N. Browder to H. O. Weeren on "Significance of Hydrofracture as a Waste Disposal Method for ORNL," July 22, 1970.

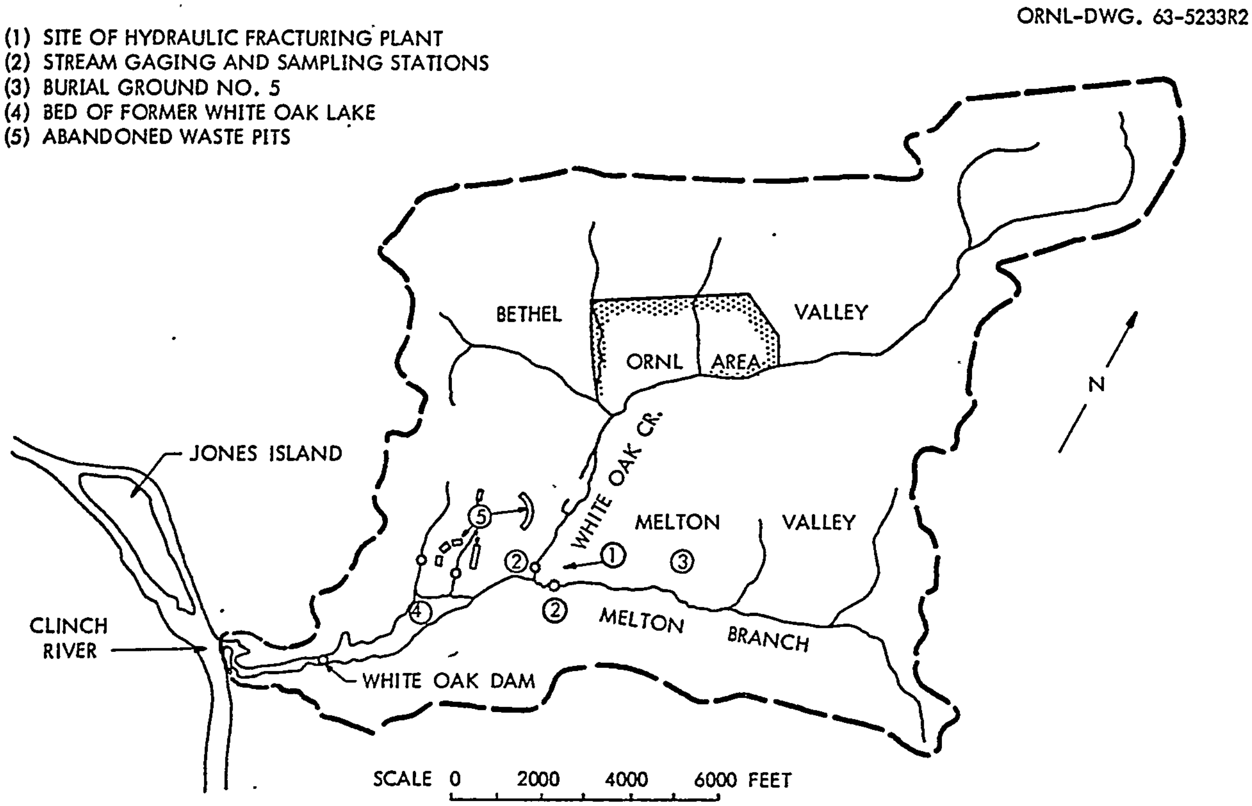

Fig. 1. Map of White Oak Creek Basin.

Rome is overlain by the Conasauga shale, about 2000 ft thick. The bottom 300 ft of the Conasauga, the Pumpkin Valley member, is dense argillaceous shale that is very thin-bedded and dominantly red. This is the unit into which all the experimental and actual waste injections have been made. The Pumpkin Valley is overlain by what is probably the Rutledge member of the Conasauga. The so-called Rutledge, about 1000 ft thick, is composed of gray calcareous shale interbedded with generally thin beds or lenses of limestone. The contact between the Pumpkin Valley and the Rutledge is marked by three beds of limestone. The Rutledge is overlain by the Maynardville limestone member of the Conasauga, generally thin-bedded and locally oolitic and fossilferous.

A diagram of the subsurface geology at the Fracturing Plant site is shown in Fig. 2. A test well has been drilled to a depth of 3263 ft at a site approximately 300 ft from the present fracturing plant. Cores from this well fixed the depth of the various geologic formations adjacent to the injection site. These data are analyzed in detail in ORNL-4259.

Hydrology

The Conasauga shale, the formation with which we are principally concerned, is weathered to a depth of 50 ft or more under the ridges, and to a depth of 5 or 10 ft in the valleys. The weathered material is permeable, although only poorly so, and contains groundwater. Wells drilled in the weathered shale will yield from 2 to 10 gpm. Very locally there is some movement of groundwater in the Conasauga along weathered joints to depths of 100 or even 200 ft, but the amount of water reaching these depths is very small and the rate of movement is very small indeed. As far as we know there is no movement of groundwater below 200 ft. Tests of the nine so-called rock cover monitoring wells described below show that the shale at depths of 500 to 600 ft is quite impermeable. The Pumpkin Valley member of the Conasauga – the red shales into which we are disposing of waste by fracturing – contains small amounts of both disseminated sodium chloride and methane gas and so must be completely isolated from the surface by a truly impermeable cover of overlying shale.

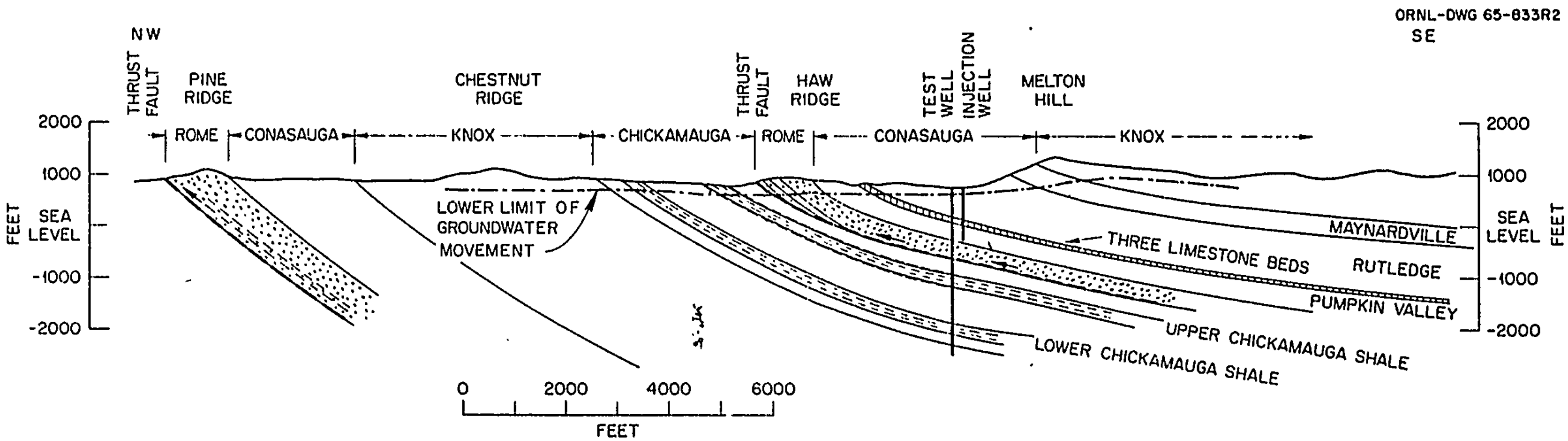

Fig. 2. Geologic section through test well at fracturing site.

Seismology

Oak Ridge is located in an area of moderate earthquake damage (zone 2). This means that on an average there will be one earthquake of intensity V (Modified Mercalli Scale), which is strong enough to be easily felt, every three years, one earthquake of intensity VIII, which is capable of doing damage to buildings of average construction, every 50 years, but there is no record of a truly destructive earthquake of intensity IX or greater. The surface structures of the disposal plant, with the possible exception of overhead solids storage bins, are compact and very strongly constructed and would not be subject to material damage from any earthquake. The shale and the contained grout sheets would move as a unit and would not be subject to damage. There is no record or evidence of any faulting in this area associated with earthquakes, so the idea that the earth might open up and expose the grout sheets to leaching has no foundation in fact. The disposal well itself is probably the most vulnerable part of the plant complex, but in the absence of faulting or landslides even the well would come through a very strong earthquake without damage. In other words, even a major earthquake would find no way to release the radioactive materials disposed of by hydraulic fracturing, and indeed in an area of very high earthquake hazard disposal by fracturing might well be the preferred method.

DESCRIPTION OF FRACTURING PLANT

Design Parameters

Experimental parameters. The hydraulic fracturing plant is situated about a mile from ORNL. As mentioned earlier, the site was chosen because the subsurface geology was known to a depth of 3200 ft, because a waste transfer line from the Laboratory was nearby, and because the site was remote enough from the Laboratory so that any release of radioactive waste solution that might occur would be much less serious than a similar leak in the Laboratory area.

There are underground shale formations at the site that are believed suitable for waste disposal injections at several depths – 692 to 1002 ft, 1642 to 1847 ft, and 2650 to 2850 ft.[5] All these formations are well below the deepest known water-bearing formations (about 200 ft). For the series of experimental injections that was contemplated, it was necessary to plan for the recovery of a number of cores of the injected grout sheets. Core drilling to depths greater than 1000 ft would require equipment not available at the Laboratory and would be considerably more expensive than drilling to shallower depths; for this reason, the shale formation between 692 and 1002 ft was chosen for the injections.

The surface operations of the hydraulic fracturing plant are basically similar to those of a well grouting job – an operation performed daily by service companies in the petroleum industry. In these operations a cement grout is mixed and pumped down a well and out into the surrounding formations by one or more pumper trucks – trucks carrying large positive displacement pumps. Typically, a single pump is capable of pumping cement grout over a range of pressures and flow rates from 700 gpm at 1000 psi to 105 gpm at 6000 psi.[6] The expected injection pressures for the hydraulic fracturing experiments (about 2000 psi) fell comfortably within the operating range of these pumps; they were therefore a natural choice for the job. It was not feasible to rent the injection pump because the radioactive waste solutions to be injected during the hydraulic fracturing experiments would contaminate the pump too badly to permit its release. For this reason, the injection pump would have to be bought. Ultimately it was decided to buy one pump and have a pumper truck standing by that could pump water through the system to clear the well for future use. Since the pumper truck would handle only water, it would not become contaminated and thus could be rented.

Three waste storage tanks with a total operating capacity of 40,000 gal were originally installed at the site of the hydraulic fracturing plant. Pumping at a rate of 200 gpm each injection would require about 3 hr. Additives were used to delay the setting time of the cement, so that it would remain pumpable for the entire period.

Each of the first experimental injections was made through a separate slot cut in the bottom of the injection well. Multiple injections through the same slot have been used for our actual disposal operations. It is still occasionally necessary to cut a new slot in the injection well, however. These slots are cut with a high-pressure water–sand jet. In this technique a slurry of sand and water is pumped down a string of tubing hanging in the injection well out a jet at the bottom of

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5. W. de Laguna and T. Tamura, *Waste Treatment and Disposal Program Report for November–December 1962*, ORNL-TM-516, pp. 58–61.

6. Technical Data Sheet, Halliburton Co., Duncan, Oklahoma.

the tubing string to impinge on the casing at that point and rapidly erode it. The "spent" sand–water slurry is recirculated to the surface through the annulus between the tubing and the casing. At the end of this operation the jet at the bottom of the tubing string is dislodged and brought to the surface. The subsequent injection of waste slurry is then made through the $2\frac{1}{2}$-in. tubing string. Such use of the center string for both injection and slotting increases the operating flexibility of the system and thereby offers some increased measure of safety.

The experimental parameters of the hydraulic fracturing plant – a semiremote location, a 1000-ft injection depth, a 200-gpm injection rate, a sand erosion technique for slotting the well, and 40,000-gal batches – were fixed by the considerations given above. For the later injections, the installation of additional tank capacity made substantially larger injections feasible. Otherwise, these parameters remain unchanged.

Injection Well

A sketch of the injection well at the hydraulic fracturing facility is shown in Fig. 3. The well consists of a 150-ft length of $9\frac{5}{8}$-in. surface casing with a 1050-ft length of $5\frac{1}{2}$-in. casing inside. The surface casing is cemented to the well hole for its entire length; the $5\frac{1}{2}$-in. casing is cemented to either the well hole or the inside of the surface casing for its entire length.

Wellhead. The wellhead arrangement used for slotting the injection well is somewhat different from the arrangement used during a waste injection. Sketches of these arrangements are shown in Figs. 4 and 5.

When waste is being injected, the wellhead assembly consists of a casing head that is screwed to the top of the $9\frac{5}{8}$-in. surface casing, a tubing head that is fitted on the top of the $5\frac{1}{2}$-in. casing and bolted to the casing head, an adapter flange that supports the $2\frac{1}{2}$-in. tubing string and is bolted to the tubing head, and a shutoff valve that is bolted to the adapter flange. Waste grout is pumped at high pressure through the shutoff valve and down the tubing string. The annulus between the tubing string and the $5\frac{1}{2}$-in. casing is valved off by a shutoff valve on the tubing head; this annulus is filled with water and is pressurized to approximately the grout injection pressure (since the tubing string is open to the annulus at the bottom of the well).

When the well casing is being slotted, the adapter flange and shutoff valve are replaced with a packoff flange and a swivel joint. The tubing string is supported during this operation by a crane outside the building. A slurry of sand and water is pumped down the tubing string under high pressure; the same sand–water slurry is withdrawn through the annulus under low to moderate pressure.

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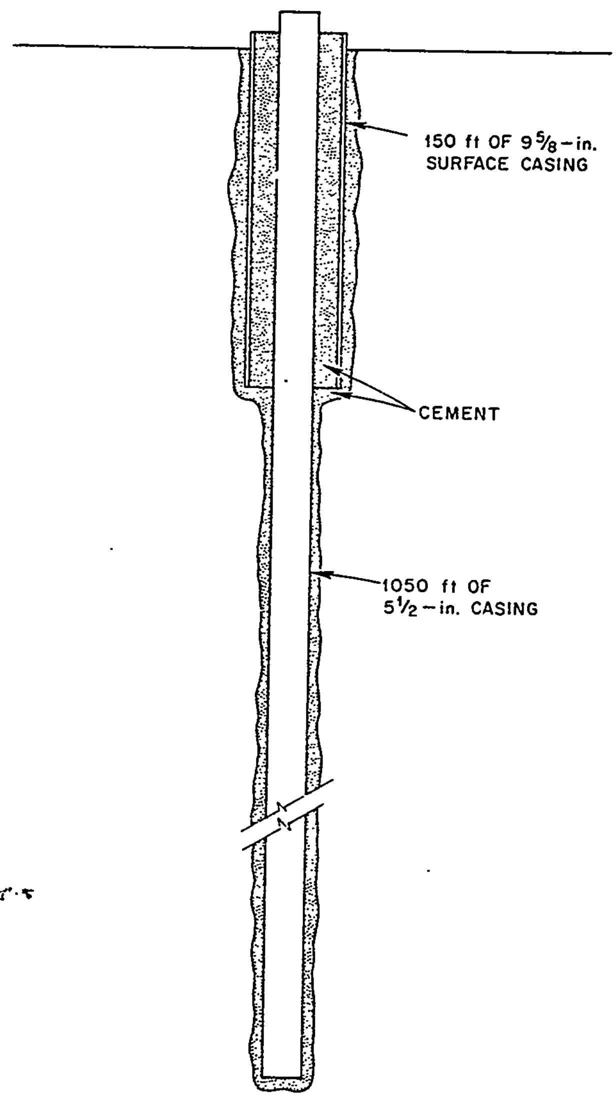

Fig. 3. Injection well construction.

Surface Plant

The equipment used for the injection of each batch of waste consists of a waste transfer pump and spare, four bulk storage tanks to store the cement and other solid constituents of the mix, a surge tank, a high-pressure injection pump, a standby injection pump and mixer, and assorted valving and special equipment. The arrangement of this equipment is shown in the flow

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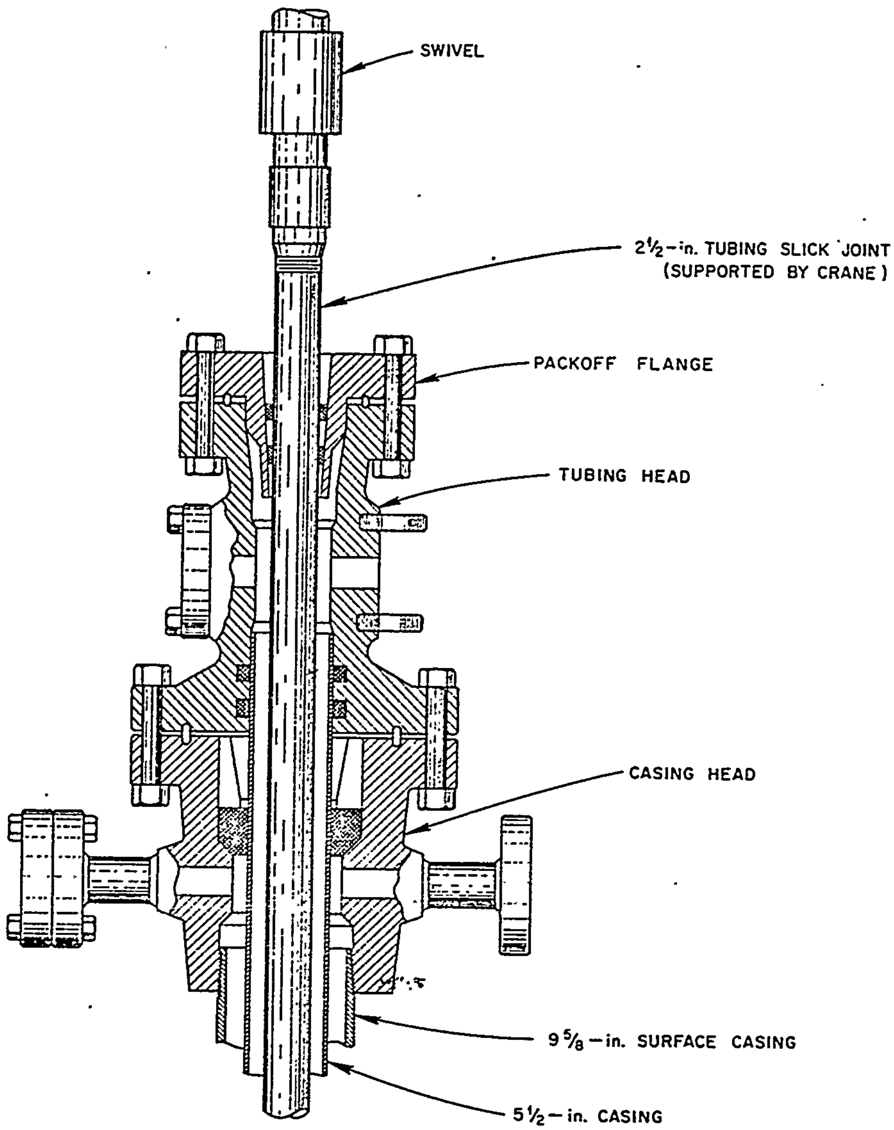

Fig. 4. Wellhead arrangement for slotting.

diagram in Fig. 6. The mixer, surge tank, injection pump, and wellhead valving are installed in cells to reduce the radiation exposure of the operators and limit the area that would become contaminated in the event of a leak in the equipment or piping. The cells are made of a 12-in. thickness of concrete block and are roofed with sheet metal. All necessary control operations are carried on from outside the cells during an injection. The principal features of the hydraulic fracturing facility are shown in their relative locations in Fig. 7.

Five waste storage tanks with a total capacity of 90,000 gal have been installed at the hydraulic fracturing plant. Prior to each injection the waste solution is pumped to the site through a waste transfer line at a rate of approximately 20 gal/min and stored in these tanks.

The waste storage tanks are installed underground in a pit partially filled with crushed rock and are covered with a minimum of 4 ft of earth. A dry well is installed by each tank so that samples of the water (if any) in the crushed rock below each tank can be obtained. Concrete block walls are used to segregate possible leakage from a tank. A drain for ground water is provided at a level 3 ft above the bottom of the pit; this drain empties into a ditch leading to White Oak Creek. This ground water drain system was adequate for the preliminary experimental injections which involved only simulated waste solutions with radioactive tracers; it became inadequate when the operational injections of real ILW wastes began and will be changed.

The waste tanks are agitated by means of air lift spargers – four in each of the first two tanks, two in the third tank, and three in each of the last two tanks. Two vent systems are provided; one services three tanks and the other services two tanks. In each system, the air stream from each tank passes through a common manifold to a high-efficiency filter and is discharged to the atmosphere through a 3-in. pipe which extends 9 ft above ground level. A pneumatic level gage is installed on each tank. The waste solution in any tank can be sampled by pumping solution from the tank of interest with the waste transfer pump, through a sampler, and back to one particular waste tank.

The waste transfer pump is a modified Moyno, Type 2L14H, with a 25-hp motor; the spare pump is identical. Either pump is capable of pumping approximately 180 gpm at 120 psi, but both pumps are usually run together. A removable strainer is provided on the pump suction line and a 250-psi pressure relief valve is installed on the discharge line. The two pumps are housed in a partially underground concrete block structure.

Most of the valves in the waste handling system are mounted in a valve pit adjacent to the pump house. This valve pit is made of concrete block and is roofed with $^3/_4$-in. grating covered with 16 gage sheet metal. The valve handles extend through the roof of the valve pit.

The addition of a small quantity of tributyl phosphate (TBP) to the waste solution was found to greatly decrease the amount of air entrained in the waste grout. Unless the amount of air entrainment is thus reduced, control of the solids-waste proportioning becomes impossible and operation of the injection pump becomes ragged. The TBP addition system is therefore vital. A minimum of 250 ppm of TBP is required for

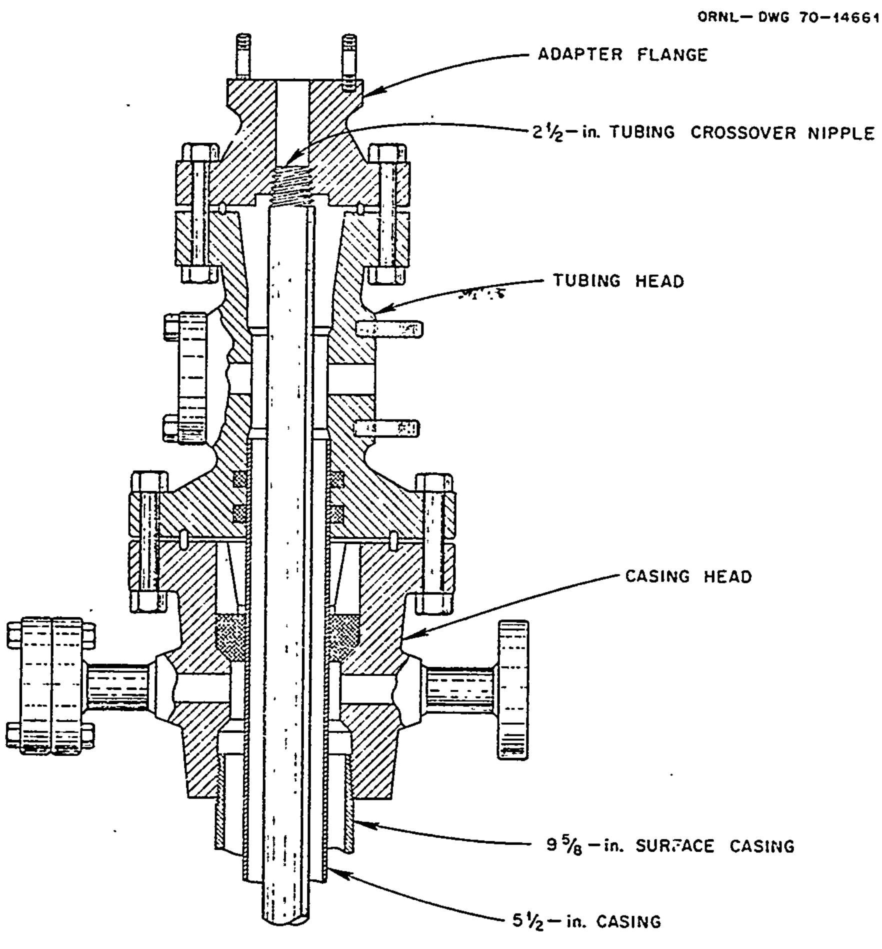

Fig. 5. Wellhead arrangement for injection.

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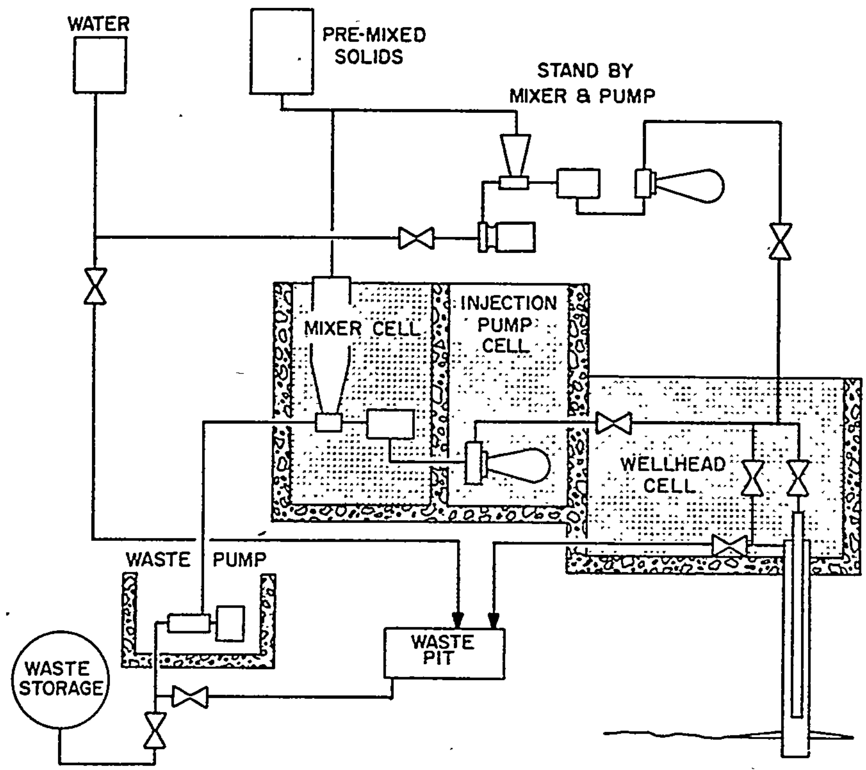

Fig. 6. Schematic flow diagram of shale fracturing experiment.

smooth operation – about 190 ml/min at full injection rate. This is added to the waste solution on the discharge side of the waste pump by means of a Milton Roy pump. Check valves in the line prevent backflow.

A week or more before an injection the solids – cement, fly ash, Attapulgus 150, Grundite, and a retarder – are brought to the fracturing site, blended in the desired proportions in a weigh tank, mixed by blowing them back and forth between two pressure tanks, and stored in four bulk storage tanks. These tanks are 12 ft in diameter and have a capacity of 2780 ft^3 each. They are installed on steel legs so that the bottoms of the tanks are approximately 6 ft above the top of the mixing cell. During an injection the solids in each tank in turn are aerated and flow through an air slide (an enclosed chute that is continuously aerated from below) into a metering hopper in the mixing cell and from there into the mixer.

The jet mixer is a device for mixing the waste solution and the solids. The waste solution is pumped through the mixer under a pressure of 100 psi; the solids drop into the mixer and are picked up by the jet stream and thoroughly mixed with the waste. The resulting grout is dumped into the surge tank. The mixer bowl is connected to the hopper to confine the solids and any grout that might splash out of the mixer. An observation window is provided.

The surge tank provides a means by which the flow of the waste transfer pump and the flow of the injection pump may be synchronized during an injection. One operator, who controls both pumps, observes the level of grout in the surge tank, either through a mirror and window arrangement on top of the tank or by observing a float-type level gage. He adjusts the flow rate of one or the other of the pumps as the grout level fluctuates. During an injection, air is withdrawn continuously from the surge tank, filtered through a high-efficiency filter, and discharged.

The control of the proportions at which solids and waste solution are mixed in the fracturing plant is critical. If the proportion of solids is too high. the resulting grout will be viscous, difficult to pump, and subject to premature setting. If the proportion of solids is too low, the resulting grout will not retain all of the

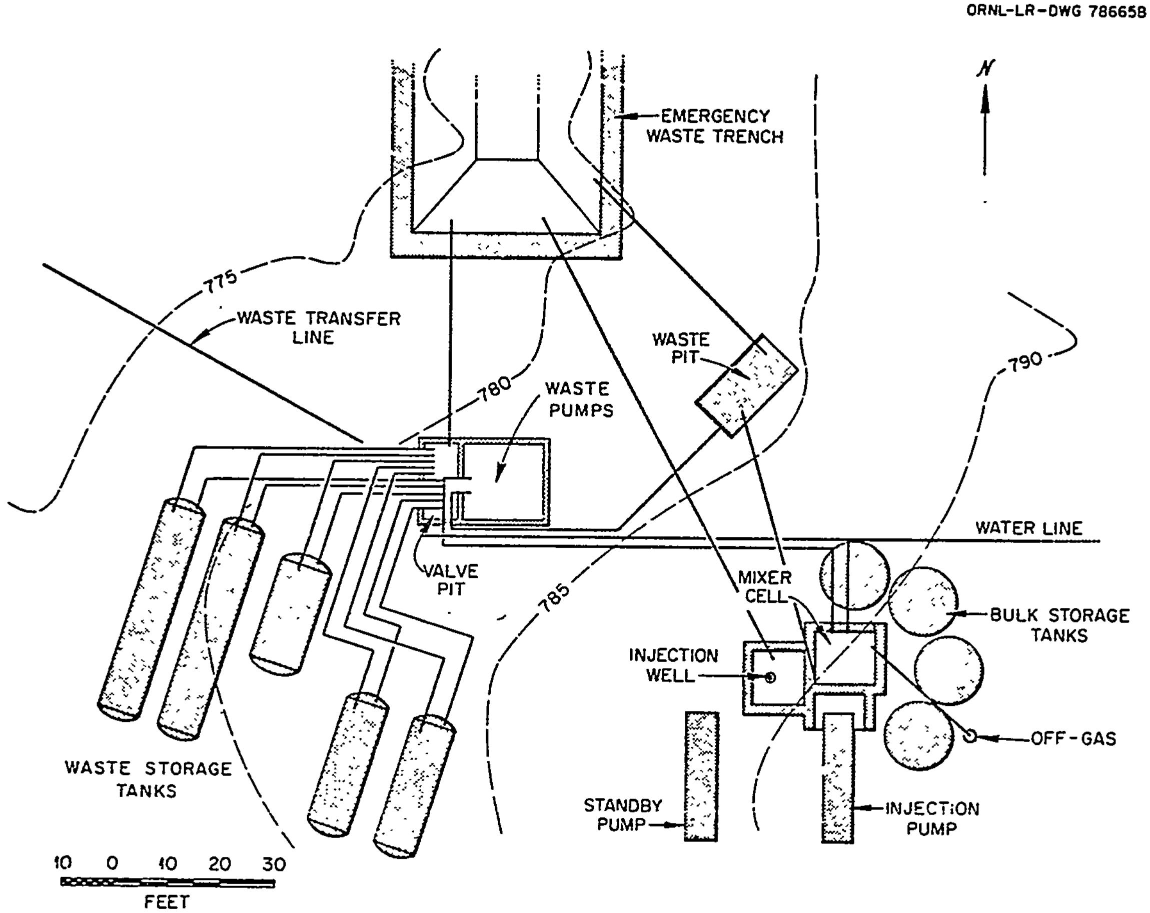

Fig. 7. Layout of the hydraulic fracturing plant.

associated liquid. When it sets "phase separation" will occur. The desirable operating range between these two extremes is fairly narrow; the variation from the desired value should not exceed 10% at most and should be kept within 5% if possible. During a waste injection, this mix ratio is controlled by manually regulating the flow of solids from the metering hopper to maintain a fixed ratio of solids addition for a given waste flow rate. The solids additive rate is measured by a "mass flowmeter" – a device that continuously weighs the flow of solids – that is installed immediately below the metering hopper. A check on the solids proportioning is provided by the Densometer system. (The Densometer is a device that continuously measures the density of the fluid circulating through it.) A small hydraulic-powered pump mounted in the surge tank continuously pumps grout from the surge tank, through one of two Densometers, and back to the surge tank.

Three cells are provided for the mixing and injecting equipment – one $12\frac{1}{2} \times 11\frac{1}{2} \times 8$ ft for the mixer and surge tank, one $10 \times 7\frac{1}{2} \times 8$ ft for the head end of the injection pump, and one $11 \times 11 \times 10$ ft for the wellhead and associated piping. All cells are made of a 12-in. thickness of concrete block and are roofed with $\frac{3}{4}$-in. grating covered with sheet metal. The cells are painted, but unlined. The roof of the mixer cell is fixed in place; the roofs of the pump cell and wellhead cell are removable. Because the process piping in the pump cell and the wellhead will be under considerable pressure (up to 4000 psi), the vision ports in these cells are made of bulletproof glass and the roof grating is covered with $\frac{1}{4}$-in. steel plate on both sides. Access to the cells is by a hatch in the roof of each.

The injection pump is a Halliburton HT-400 triplex positive displacement pump that can pump over a range of pressures and flow rates between 6000 psi and 105 gpm and 1000 psi and 700 gpm. It is mounted on a skid with a ten-speed transmission and a VT-12 Cummins diesel engine. A steel splash plate is fitted around the head of the injection pump and extends to the walls, floor, and roof of the cell, thereby isolating the pump head within the cell. Washup lines to the pump suction manifold are installed.

A standby injection pump is rented for each waste injection. It is a standard truck-mounted Halliburton positive displacement pump that is similar to the main injection pump. During each injection it is connected via the wellhead manifold to the injection well. Its function is to provide a means for flushing the injection well free of grout in the event the main injection pump fails; it is not required to pump radioactive fluids.

A piping manifold connects the injection pump, the injection well, the standby injection pump, and the waste pit. The manifold contains ten plug valves, two check valves, a pressure relief valve (set at 7500 psi), a pressure gage connection, and 13 unions. The components of this manifold are rated at 10,000 psi or more. Extra high-pressure Chiksan swivel joints are used between the injection pump and the piping manifold and the wellhead to damp vibration between the pumps and the wellhead.

A considerable volume of water is required for such operations as slotting the casing of the injection well and washing equipment after an injection. Since this water will become contaminated, it must ultimately be injected with the waste solution. To keep this contaminated water from being a significant fraction of the waste being injected, it is necessary to reuse water where feasible. The waste pit was built to serve this function; it is a concrete pit 12 ft square by 9 ft deep. Washup water and water used in slotting operations drain to the waste pit and are pumped out of the pit by the waste pump for reuse.

The emergency waste trench is a safety measure against the unlikely possibility that, late in the course of a waste injection, the wellhead might rupture, allowing the injection grout to flow back up the well with no way of stopping the flow. Should such an event occur, the grout would flow from the wellhead cell through an 18-in. line to the 100,000-gal waste trench where it would set and be covered with earth fill.

A cell off-gas system removes 900 cfm of air from the mixer cell, pump cell, and wellhead cell, through a roughing and a high-efficiency filter in series, and exhausts it out a short stack. A separate off-gas system is provided to exhaust the surge tank. This system exhausts 150 cfm through a demister mounted in the tank and two high-efficiency filters and discharges the air out a 40-ft stack.

Monitoring Wells

Two types of wells have been used to monitor the disposal operation: gamma-ray logging wells and the so-called rock cover monitoring wells (see Fig. 8). One of each, to serve as prototypes, was installed when the plant was built in 1963 and several more of each have been added since (see Fig. 9).

The prototype logging well (N 150) was installed 150 ft north of the injection well. It consists of 1050 ft of $2\frac{7}{8}$-in. steel tubing cemented into a $6\frac{1}{2}$-in. hole, with the bottom of the casing some 50 ft into the Rome sandstone. The bottom 350 ft of the casing was cemented in with a polymer water gel (PWG) cement which never sets up quite hard although it does develop considerable strength. The top 700 ft of the well was cemented in with portland cement.

This well has been intersected, as was intended, by most of the grout sheets which have been formed by both our experimental and operational injections. It is possible by conventional gamma-ray logging to pick up the point of intersection of the radioactive grout with the well, and since all these wells have been surveyed (this one was quite vertical) it is then possible to locate one point on the grout sheet in three dimensions underground.

When the grout-filled fracture intersects the well the overlying shale is uplifted by about the thickness of the grout sheet, that is, by about $\frac{1}{2}$ in., while the lower part of the casing is held firmly in place. The PWG cement, which remains slightly plastic, will give enough at the point of intersection to prevent the casing from being pulled in two, and has worked well. Unfortunately, it does permit a slight migration of radioactive fluid for a short distance above the intersection, which complicates the record slightly, but, as there is no trouble in distinguishing the grout-filled fractures because of their much larger response, no harm is done.

Late in 1964 four more core holes (NE 125, N 100, NW 100, and S 100) were drilled and later converted into logging wells by cementing in $1\frac{1}{4}$-in. tubing. This is the largest diameter tubing that can be placed in the 3-in. core hole, and unfortunately it is not strong enough for the service. These wells were cemented their full length with portland cement in an attempt to avoid the migration of fluid along the casings, but the casings of two of these wells were pulled apart exactly as had been feared. In 1968 a fifth core hole (S 220) was drilled and also cased with $1\frac{1}{4}$-in. tubing. In this case, however, the tubing was welded so that the shoulders provided by the couplings were eliminated, and the outside of the tubing was covered with automobile undercoat to prevent, if possible, a good bond between the casing and the cement. Unfortunately, these precautions were unavailing and the casing of this well also was pulled apart by the next injection. We now have seven logging wells (N 150, N 100, NE 125, NW 100, S

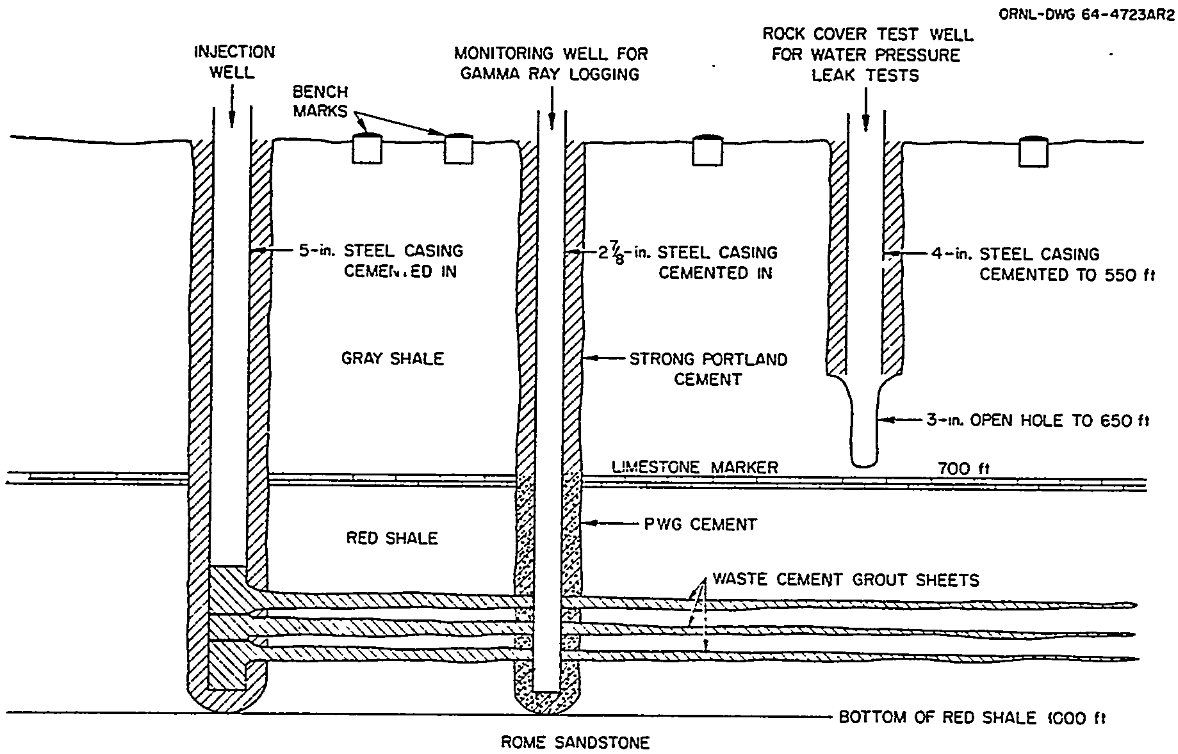

Fig. 8. Sketch showing monitoring well and rock cover leak test well.

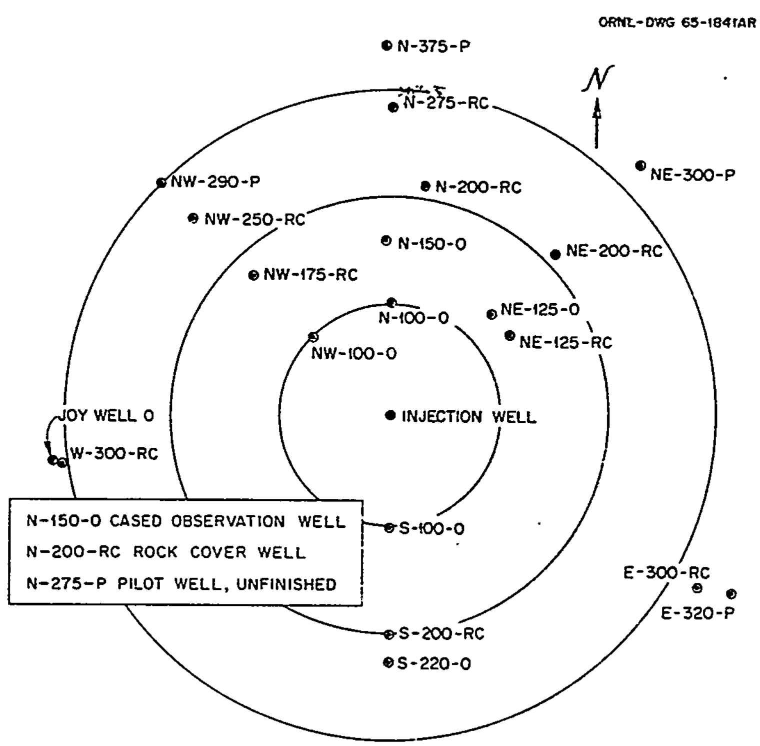

Fig. 9. Pattern of observation wells predrilled to a depth of between 500 and 600 ft.

100, S 220, and the Joy well – the deep exploratory well at W 300). Wells S 100 and S 220 cannot now be used since, when their casings were pulled apart, enough grout came in and hardened to plug them. Only a little grout came into well NW 100 when its casing parted, not enough to plug it but enough to slightly contaminate the water inside the casing.

The second type of monitoring well is the so-called rock cover monitoring well. These are constructed by drilling a 6½-in. hole down to 500 or 550 ft, cementing in a 4-in. casing, and then drilling a 3-in. open hole to a depth of 100 ft below the bottom of the casing. The original purpose for which these wells were intended was to monitor the rock cover for possible increases in permeability, and this is done by attempting to pump water into these wells at a standard pressure of 75 psi. Some of the wells when first tested accepted no measurable quantity of water; a few would take a gallon or two during the first hour of pumping, but after that would accept no more. The last of these wells, of which there now are nine, was only completed in the summer of 1969, but none of the older wells has shown any change in the cover rock.

These wells have been found to be useful in another and unexpected way. When the wells are filled to the brim with water and then equipped with pressure gages, pressure variations are observed during the course of an injection. As shown in Fig. 10, when the grout sheet passes under one of these wells the shale around the open hole section of the well is compressed and a small amount of water is forced into the well, raising the pressure. However, when the grout sheet passes to one side of the well or moves out in another direction, the shale at the lower end of the well is subjected to a shearing stress, the minute fractures present in all of the shale are slightly opened, and the pressure in the well goes down slightly. The rises in pressure are more distinct than the drops. This method gives some indication of where the fracture is going while the injection is still in progress.

Bench Marks

A third independent monitoring system is the network of bench marks installed in the area (see Fig. 11). These were constructed by augering in 18-in. holes to a depth of 8 ft, or to refusal, pouring in concrete, and inserting a metal pin in the top. The bench marks were installed not so much as a monitoring system as to study the surface uplift, which is of considerable interest in itself as it sheds light on the rock mechanics of the fracturing operation. Several rounds of leveling,

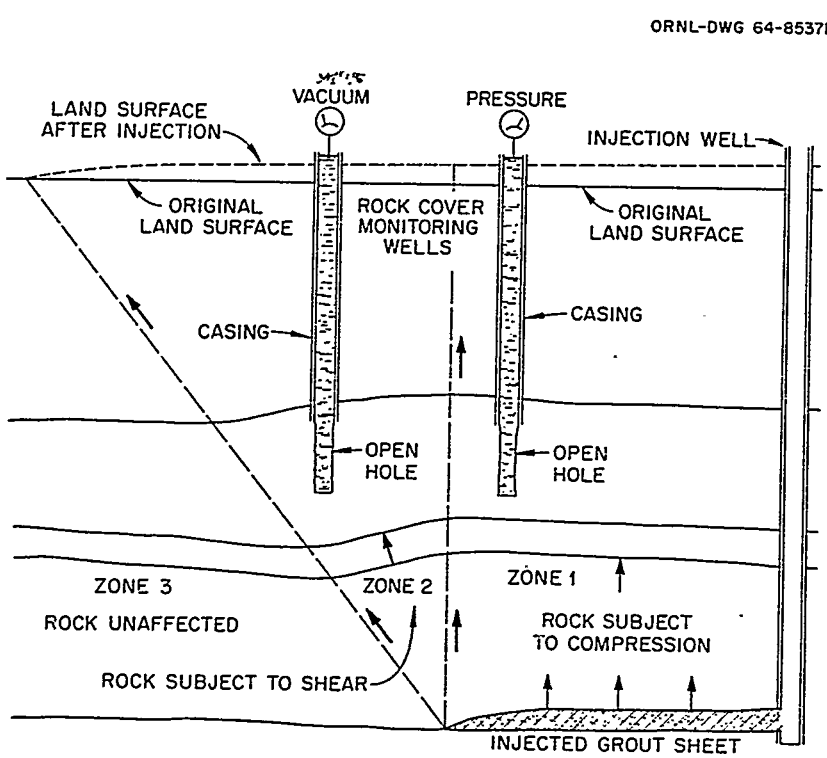

Fig. 10. Stresses in rock due to injection of grout.

made before and during the experimental injections, showed that the surface uplift formed a smooth and regular curve, over ½ in. high at the center, and extending out about 1600 ft in all directions. The smooth, regular profile of the uplift showed that the rock cover had been arched up as a unit without faulting (see Fig. 12). If, with continued repeated injections, the profile developed a break or discontinuity, this would be evidence of breaking or faulting in the cover rock. Because of the expense of the high-precision leveling required, no leveling of consequence has been attempted since 1965.

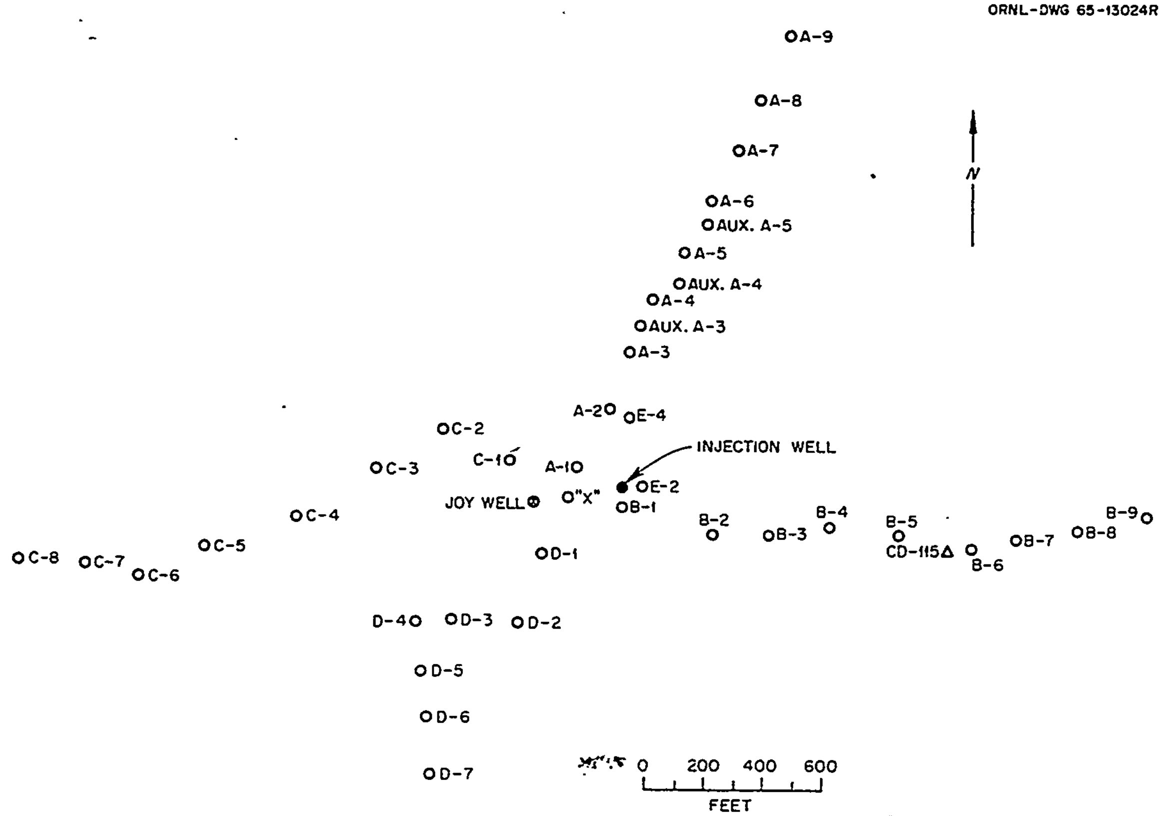

Fig. 11. Layout of leveling bench marks at the hydraulic fracturing plant.

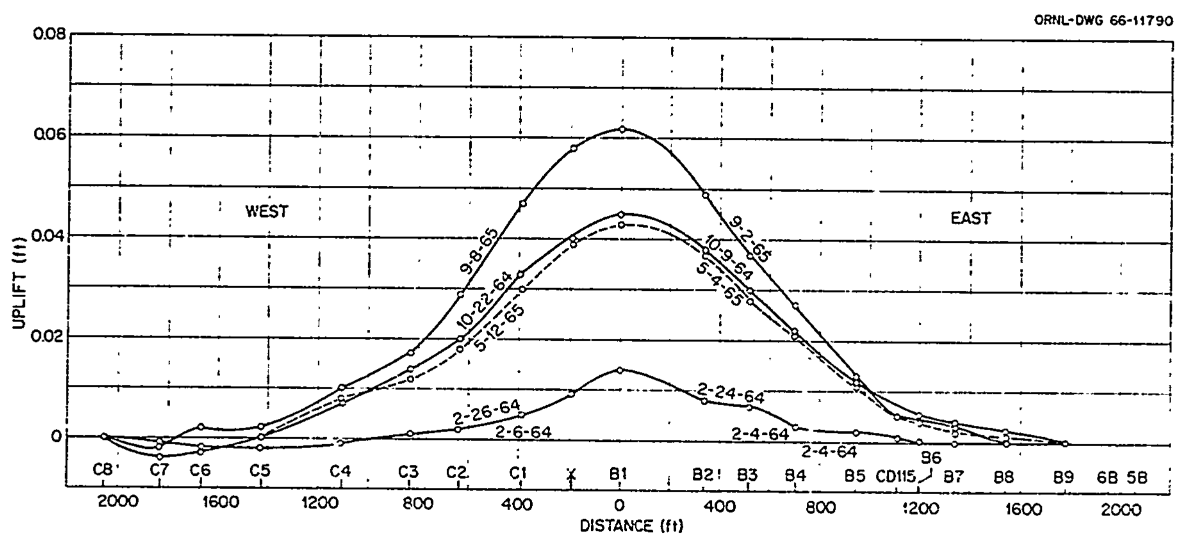

Fig. 12. Profile of surface uplift, east-west section.

OPERATIONAL EXPERIENCE

Operating Procedures

An approximate composition of the ILW waste solution disposed of by hydraulic fracturing is given in Table 1. During an injection this waste solution is blended with a mixture of solids to form a grout that will remain fluid for several hours, that will retain essentially all associated water when it sets, and that will retain cesium and strontium even after considerable leaching. The solids mixture that fulfills these varied requirements contains portland cement, fly ash (to extend the cement and improve strontium retention), attapulgite clay (to keep particles in suspension), Grundite clay (to improve cesium retention), and delta-gluconolactone (to retard setting). A typical composition for the solids mixture is given in Table 2.

Prior to transfer of the waste to the fracturing site, a sample of the waste solution is analyzed. If this analysis indicates no abnormal concentration of any component, the standard solids mix is selected for the injection.

A week or more before the injection, the attapulgite clay, Grundite clay, and delta-gluconolactone (DGL) are procured and moved to the fracturing site. Arrangements are made for cement and fly ash delivery in pneumatic transporter trucks. Cement is discharged from the transporter truck to an 820-ft^3 weigh tank until a predetermined weight has been transferred. The desired quantity of fly ash is then transferred. Attapulgite, Grundite, and retarder are then added in proportion by means of a small screw conveyer. The mixture in the weigh tank is then air blown to one of the two 800-ft^3 blending tanks. The solids are thoroughly mixed by blowing them back and forth between the blending tanks. They are then blown to one of the bulk storage bins, and another batch is mixed. This operation is continued until all the dry soils required for the injection have been blended and stored in the bulk storage bins.

Table 1. Approximate waste composition

NaOH	0.05 *M*
$NaNO_3$	0.8 *M*
$(NH_4)_2SO_4$	0.15 *M*
$Al_2(SO_4)_3$	0.05 *M*
NaCl	0.05 *M*
$NaCO_3$	0.05 *M*
^{137}Cs	0.8 Ci/gal
^{90}Sr	0.08 Ci/gal

Table 2. Typical solids composition

Cement (gypsum retarder)	2 lb/gal waste
Fly ash	2 lb/gal waste
Attapulgus 150	1 lb/gal waste
Grundite	½ lb/gal waste
Retarder (DGL)	0.003 lb/gal waste

Slotting the well. At the present time, four injections are made into a single slot in the injection well. Before the next series of four injections is made, the old slot is plugged with cement, and a fresh slot is cut in the injection well casing 10 ft above the old slot. The technique for cutting the well casing is called "hydrojet." It consists of pumping a slurry of sand and water down a string of tubing hanging in the injection well and out a jet at the bottom of the tubing string to impinge on the casing at that point. The erosive action of the sand cuts the casing and the surrounding cement and shale to a sufficient depth to make subsequent initiation of the desired fracture relatively easy. The spent slurry is brought to the surface through the annulus between the tubing and the casing, the degraded sand is allowed to settle in a waste pit, and the water is recirculated so that the volume of contaminated water produced by the slotting operation can be kept to a minimum. A sketch of this operation is shown in Fig. 13. The tubing string is slowly rotated by a hydraulic power swivel so that a complete cut of the casing is made.

The first step in the slotting operation is to remove some of the wellhead fittings and replace them with others so that the tubing string can be rotated. The tubing string is supported by a crane, and the wellhead assembly is disconnected just above the tubing head. The tubing string is lifted slightly and blocked into place. The crane releases the tubing string, and a packoff flange is fitted over the tubing string and bolted to the wellhead. Several short sections of tubing are added to the string, a hydraulic power swivel and jet catcher assembly are added, and the crane lifts and unblocks the tubing string and lowers it into position.

Water is pumped from the waste pit through the mixer and surge tank to the injection pump, which pumps the water down the tubing string, up the annulus, and back to the waste pit. When flow is established, the jet is released from the jet catcher and is pumped down the tubing string to seat on the bottom. Sand is added at the mixer and pumped through the jet at the bottom of the tubing string, up the annulus, and to the waste pit. About 25 sacks of sand are used in a typical slotting job. When the slotting

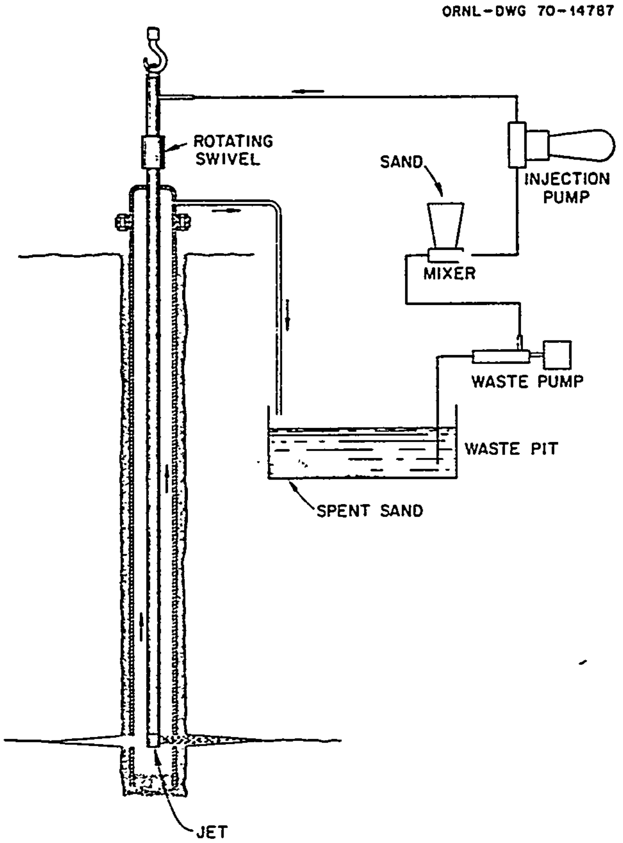

Fig. 13. Flow diagram during the slotting operation.

operation is judged to be complete, flow is reversed in the well, and the jet is pumped back up the well to be caught in the jet catcher.

The crane lifts up the tubing string about 20 ft so that the tubing will not be cemented to the bottom of the well by the next injection. The tubing string is blocked into place, the jet catcher, power swivel, and tubing sections are removed, and the wellhead assembly is rebuilt for the injection. Water is then pumped into the injection well, and the pressure is allowed to increase until the formation fractures. The initiation of the fracture is indicated by a sudden and significant drop in the injection pressure.

Injection. At the start of a waste injection, all access hatches to the cells are closed, and the off-gas blowers are turned on. One blower draws air from the surge tank and discharges it through a set of filters and up a short stack. The other blower draws air from the three cells through a filter and up a stack. Aeration of the solids storage tanks is started. The air spargers in the first waste storage tank are started, and waste is pumped from this tank to the mixer. The TBP pump is started. When the flow of waste solution reaches the mixer, the flow of mixed solids from the first of the bulk storage tanks is started. When the grout reaches the desired level in the surge tank, the injection pump is put in gear, and the grout is pumped down through the $2\frac{1}{2}$-in. tubing in the injection well and out into the fracture at the bottom of the tubing string. The pump operator controls both the waste pump and the injection pump; he adjusts one or the other of these pumps to maintain a nearly constant level in the surge tank. The cementer regulates the flow of dry solids to maintain a constant predetermined reading on the mass flowmeter. Other operators check the flow of solids from the bulk storage tanks, observe the behavior of the injection pump, keep the wellhead under observation, and switch to another waste storage tank as necessary.

Upon occasion during an injection the mass flowmeter has been found to be giving false readings; solids accumulate in the instrument and must be removed. Also, the injection pump occasionally requires maintenance during an injection, and occasionally there are other minor difficulties. The procedure followed when it is found necessary to halt an injection depends on the estimated downtime. If the downtime is to be of long duration, the flow of waste solution is shut off, and water is pumped through the system. Solids mixing is continued for a short time, and the resulting grout is injected. The flow of solids is then stopped, and the wiper plug is released and pumped down the tubing string to clear the well. The surface equipment is washed, and the necessary repairs are made in due course. If the downtime is to be of short duration, the injection is halted; but the well is not flushed, and only the germane equipment is cleaned. When repairs are completed, the injection is resumed.

When the last of the waste solution has been injected, there is usually a considerable quantity of solids remaining in the bulk storage bins. Storage of these solids until the next injection is not feasible, so they are mixed with water and injected. Some of this water is contaminated water from the waste pit, but the bulk of it is fresh water, which serves to materially decontaminate the equipment. When the last of the solids has been injected, the wiper plug is released and pumped down the tubing string with fresh water. After the wiper plug clears the end of the tubing string, a small additional volume of water is pumped down the well to "overflush" the fracture and leave it clear of grout for the next injection. The well is then shut in under pressure until the grout sets.

After the injection has been completed, the equipment is washed to remove any excess grout. This washing operation is done by first pumping water through all equipment and discharging it to the waste pit and then by hosing down the inside of the surge tank and mixer hopper.

Summary of Waste Injections and Operating Difficulties

A series of five experimental injections was made in the spring of 1964 to determine the performance of the surface plant and the underground behavior of mixes of different compositions. The significant parameters of these injections are shown in Table 3.

The first injection was made to check the operation of the surface plant and to evaluate a nonsetting mix. All subsequent injections were made with setting mixes. Various mix compositions and concentrations were used, and both concentrated and dilute waste solutions were injected. The average specific activity of the waste solutions varied from tracer level to 0.03 Ci/gal, with occasional periods when the activity was as high as 0.5 Ci/gal. The first four injections were of approximately 40,000 gal each; in the fifth injection 148,000 gal were injected to test the surface plant during an extended (11-hr) disposal operation and to determine the underground behavior of large injections.

Minor difficulties were encountered with various components of the surface plant during the series of injections; these difficulties were corrected as they appeared. In general, the operation was smooth and satisfactory.

The grout sheets were detected in the observation well during injections 2, 3, and 4 at depths that indicated that horizontal fractures were being formed. No grout sheet was detected during injection 5.

Following the injections, the formations were cored. The grout sheets of all injections were found to be essentially horizontal and parallel.

An analysis of samples of the grout sheets indicated that the grout was denser and stronger than laboratory samples of equivalent composition and that the grout was considerably stronger than it really needed to be.

The unexpected strength of the grout samples showed that the amount of cement used in a mix could probably be reduced without adversely affecting the effectiveness of the mix. Such a reduction would lead to a reduction in operating cost, since the mix cost is a substantial fraction of the total. Other data obtained at this time indicated the desirability of substituting fly ash (a siliceous material) for some of the cement in the mix so that the efficiency of strontium retention would be improved. A new mix was therefore developed – one with a low cement content and a low proportion of total solids to waste.

Experience with the first five injections indicated that the method for controlling the mix ratio that was used in these earlier injections – manual metering of solids to maintain a constant slurry density – would not be good enough to control the mixing of the low-density grouts that were contemplated for use in the next series of injections. A new solids-liquid proportioning system was therefore installed. This system consisted of a Halliburton mass flowmeter – a device that would continuously weigh the the flow of solids – installed on the solids feed stream and a liquid flowmeter installed on the waste stream. Signals from these instruments were integrated to give a direct reading of the solids-to-liquid ratio.

Two injections were planned for summer of 1965 to evaluate the new mix, check out the plant modifications, and determine the feasibility of making more than one injection into the same slot in the casing – a technique that, if successful, would probably extend the well life. Both injections were planned for a volume of about 100,000 gal, this being the maximum volume that could be injected by the existing facility without requiring cement delivery during the injection.

Injection 6 was plagued by a series of mechanical troubles: a malfunctioning flowmeter, an improperly

Table 3. Parameters of first injection series

Injection	Waste volume (gal)	Waste solution	Activity	Type of solids mix	Ratio of solids to liquid (lb/gal)	Mix cost ($/gal)
1	37,300	Concentrated	None	Nonsetting	0.63	0.01
2	27,300	Concentrated	30 Ci ^{198}Au tracer	Setting	6.5	0.07
3	33,500	Concentrated	74 Ci ^{137}Cs	Setting	13.5	0.16
4	36,000	Dilute	50 Ci ^{137}Cs	Setting	9.9	0.11
5	148,000	Dilute	4000 Ci ^{144}Ce, 150 Ci ^{137}Cs, 600 Ci ^{90}Sr	Setting	8.2	0.09

seating valve on the injection pump, lumps of caked solids in the mix, and other minor mishaps. These difficulties necessitated several temporary shutdowns of the injection; in each case after repairs had been made, the injection was resumed without difficulty. Finally, after 64,000 gal of waste solution had been injected, a crack occurred in the high-pressure piping near a bad weld, spraying grout around the wellhead cell. The injection was stopped, and the standby pump was used to pump the injection well free of grout. The wellhead cell was decontaminated, and the leaking fitting was replaced. Although much went wrong with injection 6, it did illustrate particularly well the operating flexibility of the plant – the ease with which the injection could be halted, repairs made, and the injection resumed.

Injection 7 went smoothly. The cause of the lumps found in the solids mix during injection 6 was traced to water in the fly ash used in the mix; care was taken to obtain dry fly ash for use in injection 7, and no lumps were encountered. The mass flowmeter modifications worked well and gave a more reliable indication of the solids flow during the injection than did the slurry density measurement. Calibration difficulties with the flowmeter caused the injection to be made with a solids-to-liquid ratio that was too lean, however. This resulted in considerable phase separation occurring underground.

Following injection 7, the decision was reached to convert the experimental facility into an operating facility for the routine disposal of concentrated intermediate-level (ILW) waste solution. A number of modifications and improvements were made at this time to improve various phases of the plant operation. Two additional waste storage tanks with a combined capacity of 47,000 gal were installed. The TBP metering equipment was improved, and an 820-ft^3 weigh tank was installed. This simplified the dry solids blending system and eliminated the manpower required to weigh the cement and fly ash at the cement plant. The operating area was enclosed, and the surge tank was replaced with a stainless steel tub. The electrical power supply and the off-gas system for the surge tank were improved, and. to make future decontamination easier, the interior walls were coated.

The first injection of actual waste was made on December 12, 1966, and the latest one on September 23, 1970. During the period, all of the Laboratory evaporator-concentrated intermediate-level waste was disposed of by the hydraulic fracturing method. The volumes of the waste handled, the radionuclides contained in the wastes in significant amounts, and other data for these injections are given in Table 4.

The mixture of solids used in the operational waste injections was 2 parts portland cement, 2 parts fly ash, 1 part attapulgite, ½ part Grundite, and a trace of sugar (0.055% delta-gluconolactone). Although the proportion of solids to liquids was varied somewhat between injections, the composition of the solid mix was uniform except for injections 2A and 2B when the sugar was not added to the mix. The elimination of the sugar accelerated the setting of the grout and greatly increased its viscosity. This grout was quite difficult to pump.

If allowance is made for the fact that the plant was originally built for developmental rather than operational type work, the mechanical operation of the plant has been satisfactory and better than originally anticipated. The only significant mechanical failure experienced while injecting ILW waste solution occurred during the most recent injection when the injection pump lost its prime at the end of the grout injection (this occurs at some time during every injection). In an effort to regain the prime, the operator tried to run water through the pump into the waste pit. The drain to the pit was apparently partially plugged, and the line ruptured under pressure, leaking about 100 gal of waste grout on the surface of the ground near the waste pit. The area was cleaned up with no significant exposure to operating personnel and no permanent contamination of the environment.

A constant air monitor is installed on top of the mixing cell and is operated during each waste injection. The readings obtained from this instrument after the last three injections are listed in Table 5.

For the most recent injection the airborne activity was slightly above the permissible maximum occupational exposure for a 40-hr week; the other two injections had airborne activities well below these limits. An injection is not a regular occurrence; their frequency has averaged less than two injections a year to date. For this reason the maximum permissible occupational exposure is a more rigorous standard than the facility needs to meet and the containment of airborne activity is adequate.

From the standpoint of radiation exposure, the plant has been found acceptable only because of the infrequency of its operation and remoteness from the rest of the Laboratory. All of the waste injections to date have been performed by the Halliburton Company with assistance provided by ORNL operating and maintenance personnel. The Halliburton Company has used an average of 7½ men for each injection. The average exposure of the Halliburton men has been 320 millirems per injection with a high of 800 millirems. Most of

Table 4. Waste injection data

Test no.	Date	Depth (ft)	Time required (hr)	Volume of waste (gal)	Volume of waste and water (gal)	Total volume (gal)	^{137}Cs (Ci)	^{90}Sr (Ci)	^{106}Ru (Ci)	^{60}Co (Ci)	^{239}Pu (g)	^{244}Cm (g)	Other activity (Ci)	lb solid/ gal liquid
1	Feb. 13, 1964	945	2.5		40,300	43,383								
2	Feb. 20, 1964	924	2.5		33,400	42,891							^{198}Au-30	
3	Apr. 8, 1964	912	3.5		43,090	67,944	74	1						
4	Apr. 17, 1964	900	3.0		39,070	60,137	50	1	1					
5	May 28, 1964	890	4.5		153,683	217,468	193	608	35	4			Ce-4099	
6A	May 19, 1965	880	1.0		23,200	24,470								
6B	May 22, 1965	872	11.0		68,000	96,800	1,562	330	2	1				
7	Aug. 16, 1965	872	7.5		86,550	124,961	3,358	492	2	14				
Totals of test injections					487,293	678,054	5,237	1,436	40	19			4,129	
						Intermediate level waste								
1A	Dec 12, 1966	872	3.0	36,000										
1B	Dec. 13, 1966	872	2.5	26,000	69,931	95,197	19,950	3	21	8	Not analyzed	Not analyzed		6.2
2A	Apr. 20, 1967	862	7.5	86,000										
2B	Apr. 24, 1967	862	7.5	62,000	164,800	230,405	58,500	1,050	194	442	Not analyzed	Not analyzed		6.1
3A	Nov. 28, 1967	862	2.5	31,000										
3B	Nov. 29, 1967	862	7.5	52,000	99,050	146,751	17,000	9,000	400	200	Not analyzed	Not analyzed		5.5
Water test	Dec. 13, 1967	852	7.0		44,709	44,709								
4A	Apr. 3, 1968	852	2.5	24,010										
4B	Apr. 4, 1968	852	6.0	62,180	97,090	130,675	51,900	4,300	200		17.8	Not analyzed		5.1
5	Oct. 30, 1968	842	9.0	81,800	87,110	115,174	69,400	500	300	100	18.5	Not analyzed		5.6
6	June 11, 1969	842	8.5	79,350	91,750	126,331	89,000	8,900	100	200	3.93	Not analyzed		5.4
7	Sept. 23, 1970	842	9.0	83,000	107,650	145,670	44,833	2,747	236	72	28.6	0.23		5.5
Totals of ILW injections to date				623,340	762,090	1,034,912	350,583	26,500	1,451	1.022				

the exposure has been caused by entry into the cells for cleaning and direct repair of the in-cell equipment and by cleanup operations after the injection. The most troublesome equipment has been the mass flowmeter and Densometer used to regulate the solids in the grout. Lesser exposures, which would become more serious if the plant were operated more frequently, came from the high radiation background at the Moyno waste pump building and the operating areas around the cells. The normal background in the operating area at the cells ranges between 15 and 25 mR/hr during an injection.

Phase separation and bleedback. A cement base mix that contains only 4 to 5 lb of cement per gallon of waste is too lean to retain all of the associated water when it sets. Upon standing, the grout will settle, leaving a high percentage of clean liquid on top. To prevent or reduce this phenomenon, attapulgite clay is added to the solids mix used in the waste injections. This material is an effective suspending agent for waste solutions of varying concentrations. Even with this suspending agent in the solids mix, however, if the amount of solids used per gallon of waste is too low, phase separation will still occur. This phase separation has been observed after several injections, either when the formations were cored and the excess water bled back up the core hole or when the well was deliberately opened after the grout had been allowed to set and the bleedback was measured at the wellhead. In general the percentage of phase separation that occurs is small; the few instances of large phase separation can be correlated with mix proportioning difficulties.

Available bleedback data are listed in Table 6. Those injections that resulted in significant bleedback – experimental injection 3, 6B, and 7 – were injections during which known mix proportioning difficulties occurred, so the relatively large bleedback volumes were not unexpected. The large volumes that were recovered from these bleedback operations are close to the maximum volumes that can be attributed to phase separation and indicate that in these cases very little or no free water was left in the formation at the conclusion of the bleedback operation.

Grout sheet spacing. All the waste to be disposed of over the life of the well could be forced out into the shale through a single slot, care being taken at the end of each injection to pump a little clear water so that the slot itself would not be plugged. However, this would

Table 5. Airborne activity in the plant during the most recent injections

Injection date	Waste activity (Ci/gal)	Airborne activity (μCi/cc)			% of alpha activity		
		Beta-gamma	^{90}Sr	Alpha	^{244}Cm	^{239}Pu	^{238}Pu
October 1968	0.81	1.9×10^{-10}	[illegible]	2.5×10^{-13}			
June 1969	1.07	5.9×10^{-10}		1.6×10^{-12}			
Sept 1970	0.57	3.0×10^{-9}	8×10^{-10}	6.5×10^{-12}	58	20	22

Table 6. Recovery of water following waste injections

Injection	Slurry volume (gal)	Water recovered (gal)	%	Core hole or injection well	Ci recovered		% recovery	
					^{90}Sr	^{137}Cs	^{90}Sr	^{137}Cs
Experimental								
3	68,000	5,400	8	Core hole	0.001	0.008	0.02	0.01
5	217,000	None		Core hole				
6B	96,800	17,000	17.6	Well	1.1	1.1	0.3	0.1
7	125,000	20,600	16.5	Well	0.2	0.8	0.1	0.1
Operational								
2	230,000	6,000	2.6	Well				
4	132,000	1,500	1.1	Core hole	3		0.1	
7	387,000	8,000	2.1	Well	11	8.0	0.09	0.004

concentrate the stress in this one part of the rock column with a consequent increased danger of rupturing the cover rock. To reduce the possibility of failure of the cover rock, therefore, the slot is periodically plugged and a new slot cut at a higher elevation. A spacing of 10 ft between slots has been adopted because it separates the grout sheets sufficiently so that they may be individually identified in the well logging. The amount that can safely be pumped into one slot is not positively known. Halliburton at its home office in Duncan, Oklahoma, has put 40 or more injections of cement grout into a single slot in a test well. Although the circumstances are different here, a total of four injections per slot is certainly very conservative. By putting four injections into one slot, each injection consisting of about 125,000 gal, each slot will thus receive 500,000 gal and last for two years. This means that the remaining disposal formation (852 ft up to 700 ft) will suffice for 15 more slots, about 7,500,000 gal of grout over the next 30 years.

Extent of the grout sheets. The approximate location and area of the grout sheets can be inferred from the pressure behavior of test wells drilled in the vicinity of the operation. In general the grout sheets cover an elliptical area extending out from the base of the well. The orientation is not necessarily symmetric about the injection well. Typically the grout sheet from a 100,000-gal injection would cover an area of about three acres and extend a distance of up to 600 ft from the well. The dimension of the grout sheet can be determined by core drilling; however, unless appropriate bleedback procedures have been followed, it is possible that some liquid water under pressure may be associated with the grout. Consequently, precautions to prevent the escape of this water up the core hole must be taken.

Injection pressures. There are three pressures which are of significance during an injection: the breakdown pressure, the pressure required to maintain the injection after several hours of pumping, and the so-called instantaneous shut-in pressure. The breakdown pressures observed so far have varied erratically from a high of 4300 psi to a low of 1500 psi, determined probably by the local strength of the shale into which the slot had been cut. Reentry into the same fracture requires about the same pressure as the initial entry. so the actual fracturing of the shale is apparently less of a factor than the pressure required to force open the rock walls to gain access for the liquid. In any case all of the breakdown pressures have been substantially greater than the weight of the rock cover, which, as observed at the surface in the stagnant water-filled annulus, is the depth of the fracture in feet times 0.715. If the breakdown pressure were less than the weight of the rock cover, the fracture would have to be vertical.

Once fluid has started into the fracture the wellhead pressure drops, in most cases, rapidly at first and then less and less rapidly. It probably continues to drop very slowly as long as the injection continues, but for all practical purposes it will appear to have stabilized after a few hours. In our injections to date these stabilized pumping pressures have varied from 1200 to 2300 psi so that all of them are well above the weight of the cover rock. Figure 14 shows the behavior of wellhead pressure during several injections. Any unexplained departure from its general pattern of observed pressures would call for shutting down the injection until an investigation had been made. So far nothing of this sort has happened.

The instantaneous shut-in pressure, as the name implies, is measured immediately after pumping has stopped. The principle appears simple – to measure the pressure in the fracture without the effect of friction – but in practice the pressure drops rapidly once pumping has stopped and no two people would record the same value. In general, the instantaneous shut-in pressure is some 200 to 300 psi below the stabilized pumping pressure.

Summary of Monitoring Operations to Date

Gamma-ray logging wells. Monitoring of the gamma-ray logging wells has shown that, in general, the fractures formed by the various injections have followed the bedding. Those fractures do, however, move up or down as much as 10 ft in moving out 300 ft and in a few cases will intersect or cross over earlier fractures. These deviations from the horizontal are quite different from vertical fracturing in that the grout sheets continue on out horizontally, or even go downward after getting past the barrier that deflected them. All of the fractures remain well within the red shale, which is the disposal formation. A general pattern of fractures formed is shown in Fig. 15.

Rock cover monitoring wells. As already indicated, tests at different times of the rock cover monitoring wells showed no change in the permeability of the shale. Some of the wells took a gallon or two of water in the first hour at a pressure of 75 psi and some took none at all, but after the first hour none of the wells would take water.

During the course of an injection the wellhead pressure in the water-filled wells changed slowly, although virtually no change could be seen in one or two. Figure 16 shows the changes observed in the nine wells during the injections of ILW 7 on September 23, 1970. The interpretation of these changes is that at first the grout sheet moved out to the northeast, arriving under well NE 200 after about 50 min. Next the grout sheet moved out to the northwest, arriving under well NW 250 after about 310 min. Near the end of the injection the grout sheet moved out to the northeast and north, arriving under well N 200 after about 420 min, and under adjacent wells a few minutes later. No grout sheets moved out to the east, south, or west.

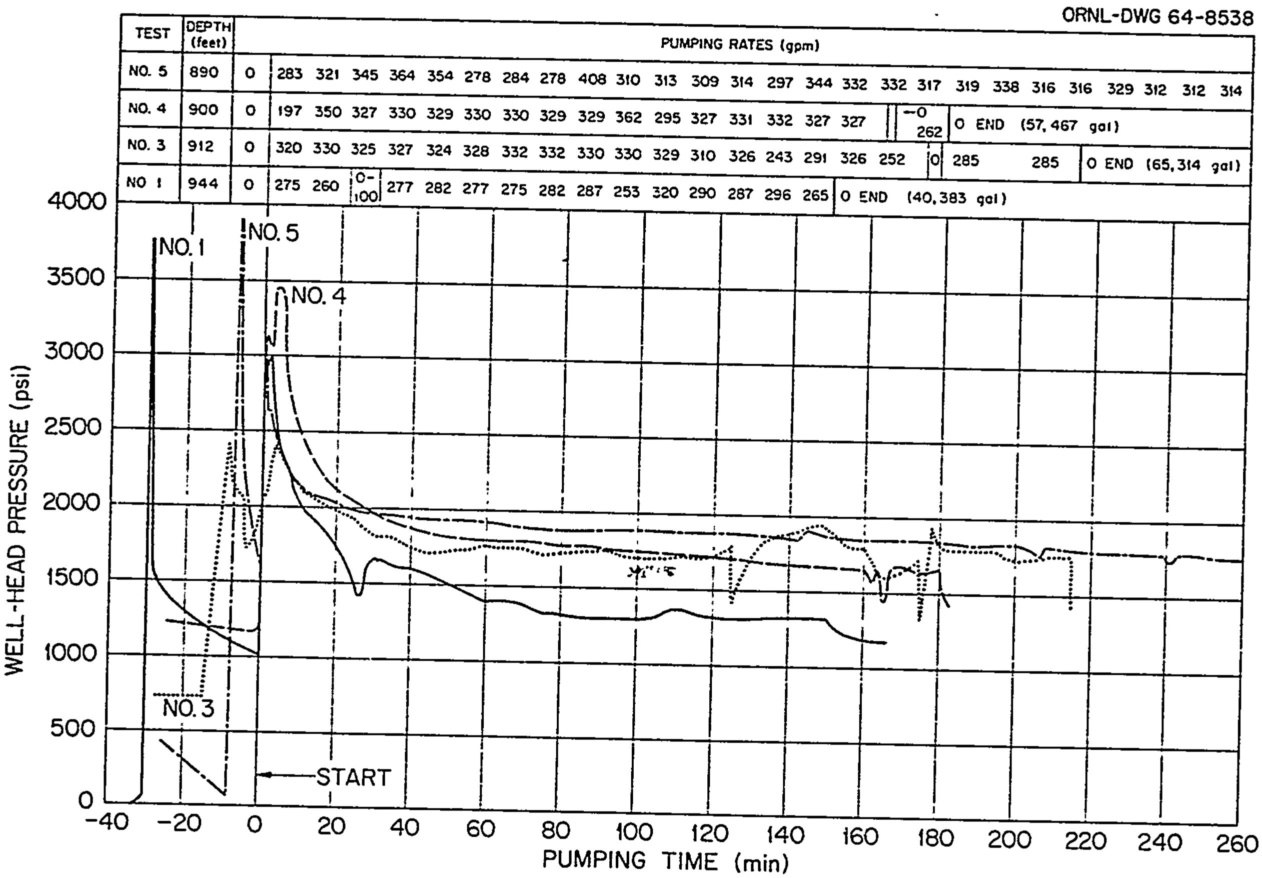

Fig. 14. Pumping pressures for injections 1, 3, 4, and 5 (measured on stagnant annulus of injection well).

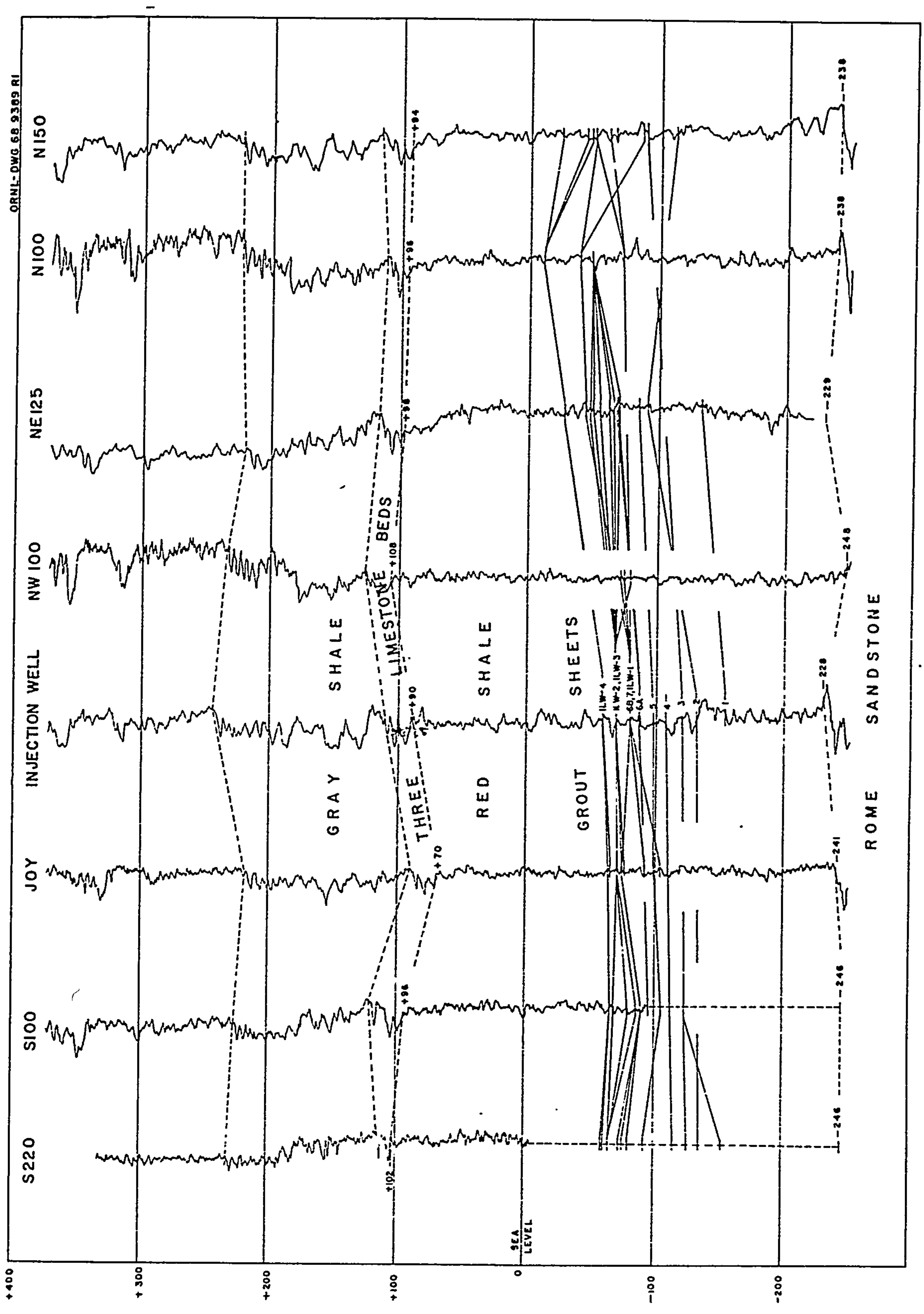

Fig. 15. General pattern of fractures.

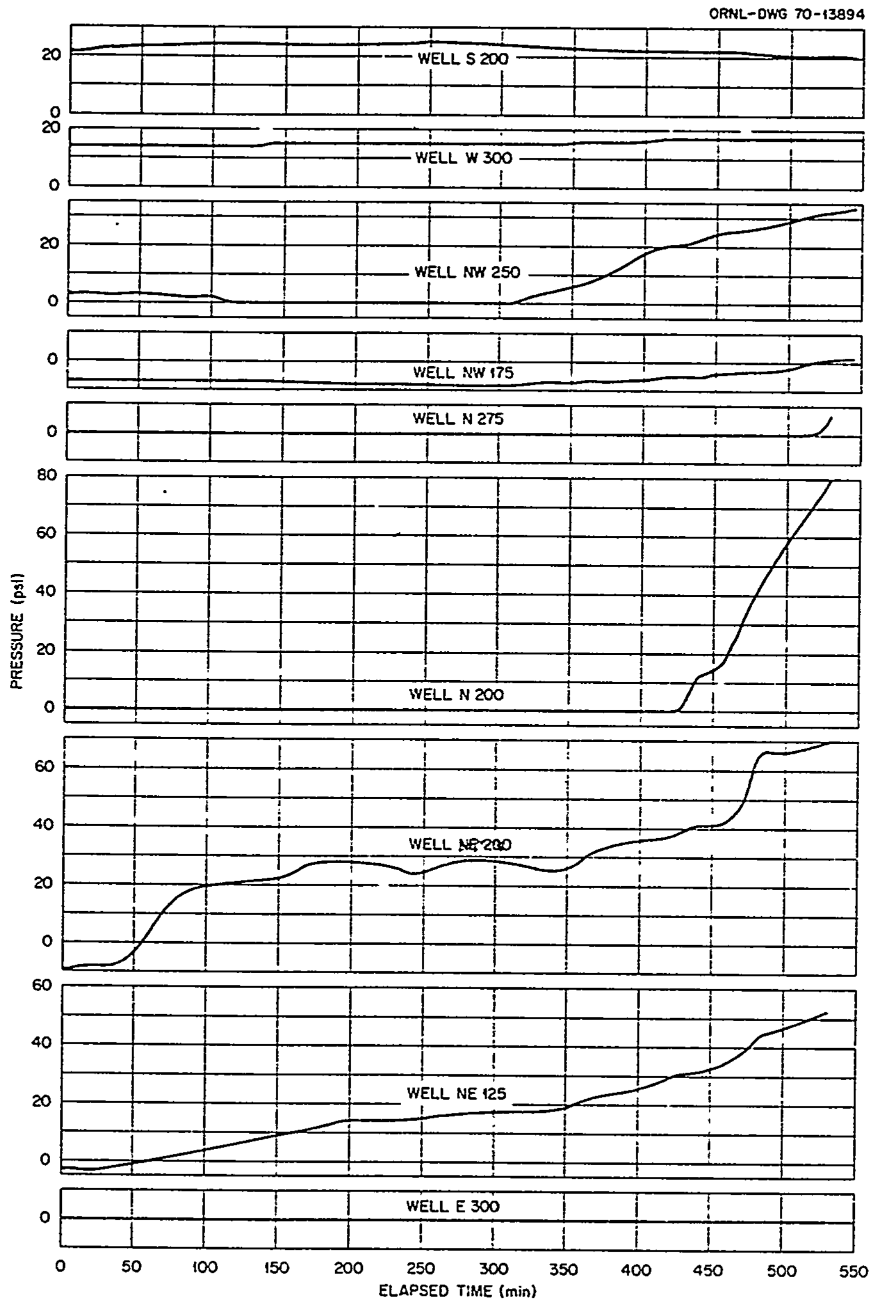

Fig. 16. Pressure variations in nine rock cover monitoring wells during injection ILW-7.

SAFETY ANALYSIS

This safety analysis of the hydraulic fracturing operation is based throughout upon the configuration of the plant as it presently exists for the disposal of current ORNL ILW wastes. Although our investigation disclosed a number of areas where significant improvements, both in safety and operability, could be made, no attempt is made to specify these in this part of the report. For the most part they will be obvious to the reader, and a discussion of the desirable improvements required to upgrade the plant from essentially a pilot operation to a routine disposal facility is included in the next section.

With few exceptions, the hazards considered in the present analysis arise because of the radioactive nature of the waste being handled, and for the purpose of the analysis, it is convenient to divide these into three categories as follows:

1. Hazards associated with preinjection operations. This category includes the low-pressure operations involved in the transport and storage of the waste solution, as well as the mixing operations which take place prior to and concurrent with the waste injection.
2. Hazards associated with the injection. This category includes the high-pressure operations which take place during the injections.
3. Hazards associated with the underground radioactive grout. This category covers those problems, both real and fancied, which could possibly arise in the future because of the presence of radioactive waste in the underground rock.

The first two categories are concerned with hazards which, if they indeed exist, may be regarded as "removable," that is, they are related to the maloperation of ordinary mechanical and hydraulic equipment. Such equipment can be made as reliable as necessary by adequate design and quality assurance procedures. and the reliability can be confirmed by tests and inspections. Accidents due to human error can be reduced in severity or eliminated altogether by employing appropriate procedures and administrative controls and by incorporating, with sufficient redundancy, proper interlocks and fail-safe devices into the design of the facility.

The third category, which is perhaps of most interest, particularly to the uninitiated, is also concerned with hazards which are removable or which may be minimized if proper care is taken to select an appropriate geological formation for the fracturing disposal operation. It differs somewhat from the first two categories in that equipment design and operating deficiencies can be detected and corrected whereas the waste-bearing slurry, once it has been pumped underground and allowed to set up, cannot be retrieved.

Hazards Associated with Preinjection Operations

Virtually all of the problems in this category are conventional in nature and are similar to those encountered in any transfer operation involving radioactive material. They can be reduced in severity or eliminated altogether by appropriate changes in equipment.

Pipeline leaks. The low-pressure process lines which carry radioactive waste solution are installed either underground or in enclosed pits or cells. A break in one of the underground lines would result in the loss of some quantity of waste solution to the ground. This is a hazard shared with other waste transfer lines, and it seems no more serious here than elsewhere in the Laboratory Complex.

A break of one of the low-pressure lines inside a cell or in the valve pit would result in the discharge of a considerable quantity of radioactive fluid over equipment, piping, and anything else in the vicinity. The cells and valve pit are so constructed that there is no direct path for the escape of any fluid: any leaked material would be contained and eventually cleaned up according to the emergency procedures developed for such an eventuality. Operating procedures require that all operators be outside the cells and the valve pit, and that the cell hatches be closed whenever waste solution is being pumped: hence, the hazard to personnel likely to result from a broken low-pressure line within the cell or valve pit is slight.

The hydraulic fracturing facility shares with ORNL's existing waste transfer system the hazard of waste leaking into White Oak Creek from a break in the transfer line that crosses under the creek. Safeguards against this possibility include the normal procedure of pressurizing the line prior to each transfer in order to detect the presence of major leaks and the monitoring of the creek a short distance downstream of the crossing. In the latter connection the background of 1.36×10^{-6} μCi/ml in the creek would be doubled by a leak of ~0.1 ml/min of 1 Ci/gal waste. Finally, White Oak Creek empties into White Oak Lake which is monitored and controlled by the Laboratory so that any appreciable increase in radioactivity would be observed at White Oak Dam.

Leaks in the storage tanks. The five carbon steel waste storage tanks are located underground approximately 100 ft west of the injection well. While fluid which is corrosive to steel is not stored in these tanks, they are subject to leaks as are any other tanks. It is worth noting, however, that these vessels are used primarily for temporary storage and contain significant quantities of activity only immediately before and during the hydrofracturing operation.

Four dry wells are provided for leak monitoring. These are sounded periodically when the tanks are in use, and should a leak be detected, the contents of the offending tank can be transferred to an empty tank if one is available or back through the waste transfer line to the ORNL Tank Farm.

In connection with the hazards associated with leaks, it is worth noting that for several years waste was disposed of by merely storing in open pits excavated in the shale near the present hydrofracture site. Experience has shown that this material is an excellent exchange medium for the ions involved and that the activity does not migrate any distance from the pit area.[7]

Plugging the jet mixer. It is possible for the jet mixer to be plugged by a sufficiently large piece of caked cement or by some foreign object. In such a case, the liquid flow would be diverted upward in the mixer hopper resulting in considerable splashing and scattering of material. To reduce the severity of such an occurrence, the hopper has been enclosed in a metal shield to contain the splashing. In any case, the spread of activity from such an accident would be confined to the closed mixer cell and would not result in contamination of any other area. Appropriate decontamination procedures would, of course, be required.

Airborne activity. Several days before each injection is to take place, each of the waste storage tanks is agitated by air sparging and then sampled. The air flow rate required for sparging is 16 cfm per tank. Data on aerosols formed by vigorous mixing of solutions and air indicate that the concentration formed by sparging will initially be of the order of 10 to 15 mg/m^3 and after several changes of air direction will be about 10 mg/m^3. The effluent from high-efficiency-type filters has recently been calculated to be 0.02 mg/m^3 for rather pessimistic assumptions.[8] For 1 Ci/gal waste solutions containing 90% ^{137}Cs, 10% ^{90}Sr, and 0.002% ^{239}Pu, the activity in the filtered effluent will be 4.8×10^{-9} μCi/cm^3 of ^{137}Cs, 5.3×10^{-10} μCi/cm^3 of ^{90}Sr, and 1.06×10^{-13} μCi/cm^3 of ^{239}Pu. Assuming pessimistic meteorological conditions (F stability and a wind speed of 1 m/sec) and that two tanks are being sparged at once, the rate of emission would be 0.00008 μCi/sec and the plume center line concentration would have dropped off to about 4.5×10^{-12} μCi/cm^3 at 100 m from the vent and to about 2.0×10^{-15} μCi/cm^3 at 1 km from the vent. Thus, while the calculated concentration in the filter effluent is slightly above the occupational maximum permissible concentration (MPC_a) the atmospheric concentration drops below the occupational MPC_a at a small distance from the vent. Moreover, since the sparging operation is carried on for 8 hr or less before and during each injection, the total inhalation exposure which could be received by directly breathing the filter effluent is equivalent to an inhalation exposure of about 2 days at the occupational MPC_a. The foregoing calculations would, of course, require modification for different waste concentrations and for different compositions.

Hazards Associated with the Injection

The most serious problems which could arise in connection with the hydrofracture operation are those associated with the injection itself. This is basically because of the use of high pressure to force the radioactive waste underground.

Spread of contamination during the slotting operation. At the conclusion of each slotting operation, which occurs every 4th injection, the tubing string in the injection well must be lifted about 20 ft to position the bottom of the tubing string above the slot through which the injection will be made. This operation requires the handling and removal of 20 to 30 ft of wet tubing that will be contaminated to some extent. The hazard due to direct radiation is negligible; the only real problem is the possible spread of contamination. It is estimated that for operations at the present level the total amount of ^{90}Sr adhering to the 30-ft length of tubing would be less than 14 μCi, and the amount of ^{137}Cs would not exceed 150 μCi. If it is assumed that 10% of this became airborne, the air concentration might approach occupational MPC. This operation does not, therefore, involve a serious hazard, and its severity can be reduced to any desired level by employing proper remote handling techniques.

Failure of services. A power failure at the plant site would affect the waste pump, the water pump, the Densometer pump, and the lights. Failure of these items would force a halt in the injection but would not cause a serious hazard, since the injection pump and the standby pump are not dependent on outside power and

7. F. T. Binford, *An Analysis of the Potential Hazards Associated with the Disposal of Radioactive Waste in Open Pits at ORNL*, CF-60-5-63.

8. Anonymous, *Siting of Fuel Reprocessing Plants and Waste Management Facilities*, compiled and edited by the staff of Oak Ridge National Laboratory, ORNL-4451 (1970).

would not be affected. If the power failure were temporary, the wellhead would be valved off and the injection pump shut down until pumping could be resumed. Alternatively, if the power were likely to be off for a considerable time, the injection could be terminated. Water from the storage tank would be used to feed the standby injection pump, which would force the slurry in the well down into the fracture; the well would be sealed off, and the equipment would be washed. Failure of one air compressor would not be serious since a spare compressor is always provided. Failure of both compressors would force a halt in the injection but would not cause serious difficulties; the injection could be terminated, if necessary, in the same fashion as after a power failure.

Break in a high-pressure line. A rupture of a high-pressure line inside a process cell, as was the case for the low-pressure lines, would result in the spraying of slurry inside the cell until a pump was shut off or a valve closed. Since the operating procedures require that the hatches be closed and the cells be unoccupied during pumping operations, this hazard is no more serious than that associated with the rupture of a low-pressure line within the cell. Cleanup would be accomplished using appropriate safety precautions developed for the purpose. There is, however, in the case of the high-pressure lines, the additional hazard that a rupture might occur suddenly enough that a fragment of high-pressure pipe would be given sufficient energy to penetrate a wall, a window, or the roof of a cell, and thereby release contamination outside the cells. To guard against this hazard the windows in the pump cell and the wellhead cell (the only cells to contain high-pressure lines) are made of bulletproof glass, and the roof grating is covered with ¼-in. steel plate. The largest unrestrained piece of equipment that seems likely to become a missile is a fragment of the plug container, which is on top of the wellhead cell. A calculation of the maximum probable impact force of this fragment gives a value (22,500 lb) well below the yield strength of the roof structure (about 50,000 lb). The impact force of a similar fragment against the cell wall is also far below the force necessary for penetration. The calculation of the maximum probable kinetic energy of a small metal fragment directly against the ¼-in. roof plate gives a value of 114 ft-lb/in.; literature values indicate that at least 1400 ft-lb/in. is required to penetrate a ¼-in. plate. It is concluded, therefore, that there is little danger of the cell integrity being breached by a missile. Details of these calculations are given in ORNL-TM-1003.

During experimental injection 6 a leak did occur in a high-pressure line at the wellhead. No pipe fragments were formed, but the wellhead cell was sprayed with waste-cement mixture. This was cleaned up with surprisingly little difficulty and with no overexposure to personnel.

There are two cases in which process lines extending outside the cells may be subjected to high pressure: (1) the operation of the standby pumping equipment will pressurize the line between the standby pump and the valve rack in the wellhead cell and (2) the slotting of the casing prior to every 4th run, which has to be done with high-pressure wellhead connections extending through hatches in the roof of the wellhead cell. The first of these operations involves no radioactive material; the second involves the use of slightly contaminated water.

Although the radioactive hazard is negligible, both of these operations possess the safety problems inherent in all high-pressure operations. These problems are common to similar operations in the petroleum industry; they may be reduced to any desired level by the use of appropriate procedures and equipment.

Wellhead rupture. The worst single hazard associated with an injection is the possibility that fittings at the wellhead may break off right at the wellhead, thereby permitting some, or all, of the waste slurry that has been injected into the well to flow back up the well into the wellhead cell with no way of shutting off the flow. Depending on the nature of the break at the wellhead, this flow could be up the tubing string, up the annulus between the tubing and the casing, or conceivably, but very unlikely, up both the tubing and the annulus. This hazard will be most severe near the end of an injection, when the volume of waste that has been injected is at a maximum.

The maximum flow rate back up the well will be determined by the pressure at the bottom of the well and the pressure drop in the well. In this analysis the wellhead injection pressure is assumed to be 1700 psi. The flow up the well, then, is that flow required to produce a pressure drop of 1700 psi. The slurry is a non-Newtonian fluid with n' and K' factors of 0.5 and 0.01 respectively.[9] The calculated pressure drop of this fluid at various flow rates in both the annulus and the tubing is shown in Fig. 17. From this curve, the maximum flow in the tubing is found to be 730 gpm, and the maximum flow in the annulus is found to be 1320 gpm. The actual flow rate would be less because these calculations take no account of friction losses and pressure drop in the fracture.

9. Halliburton Co., *Chemical Research and Development Report for October 1965*.

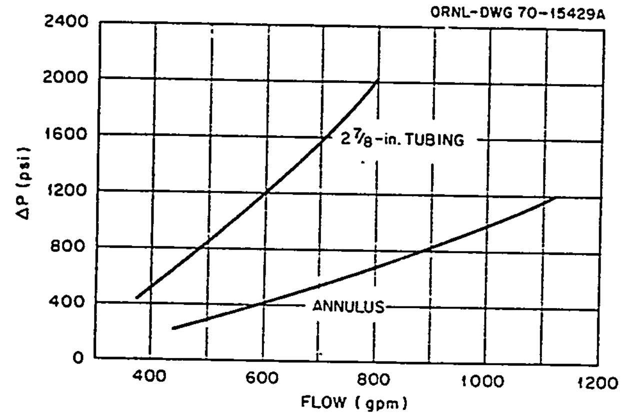

Fig. 17. Calculated pressure drop of slurry in the tubing and annulus of the injection well at various flow rates.

In the event that an accident such as that described above causes the slurry to be discharged into the wellhead cell, an 18-in. drain line has been installed from the floor of the wellhead cell to the nearby emergency waste trench. This line is 130 ft long and drops 22 ft in this distance. The calculated pressure drop in this line, at a flow of 1500 gpm, is approximately 1 psi. Two water lines have been installed in the wellhead cell to assist in washing the slurry down the drain. Once the slurry has been washed into the waste trench, it can be allowed to set there and be covered over at leisure.

Rupture of the well casing below ground. Because of its construction, it is extremely improbable that a break in the well casing below ground could occur. The existence of a break in the well casing would go undetected if the slurry continued to move down the well past the break and out into the fracture as planned. In this case the break would be of no consequence.

On the other hand, if the slurry moved out of the well at the point of the break this would be signaled by a significant decrease in pressure at the wellhead.

Breakdown pressures at 800 to 900 ft are typically of the order of 2500 to 3500 psi, and injection normally proceeds at flows of 250 to 300 gpm with wellhead pressures of 1500 to 2000 psi. Assuming a specific gravity of 2.65 for the rock cover, the weight of the rock represents a pressure of about 1000 psi as measured in the fracture or 643 psi as measured at the surface. Thus, should the wellhead pressure fall below 643 psi, it would indicate injection at some higher level or some other unexplained anomaly. As a practical matter, any unexplained significant pressure or flow change is cause for cessation of the injection until the cause is found and corrected.

Even if a break in the wellhead casing should occur, little or no hazard would result. Either the grout would be injected into the shale at a higher level than was originally planned, or it would work its way to the surface near the wellhead. In either case, the condition would be quickly detected by the accompanying pressure change.

Radiation exposures during injection. The dose rates at several locations in and around the fracturing plant were measured during experimental injection 6 and operational injection 1. These dose rates were obtained from film badge readings and were corrected for background activity where necessary. As the concentration of airborne activity was quite low, most of the measurements were from direct radiation.

The activity of the waste solution handled during injection 6 averaged about 0.1 Ci/gal of ^{137}Cs. The measured dose rates were all quite low – most were nearly indistinguishable from background. Over the valve pit, the reading was 32 mR/hr, in the waste pump house the reading was 12 mR/hr, and in the operating areas the reading was less than 15 mR/hr, in most cases much less.

The activity of the waste solution used in operational injection 1 averaged about 0.3 Ci/gal of ^{137}Cs. The measured dose rate readings were significantly higher than during injection 6 but still comfortably low in most operating areas. Some of the highest readings were: over the valve pit 164 mR/hr, in the waste pump house 112 mR/hr, and at the cementer's station 110 mR/hr. Exposure rates at various locations are shown in Table 7.

Since operational injection 1 was made the specific activity of the waste solution has increased threefold, and the dose rates have gone up proportionally. The average personnel exposure to the crew engaged in making the injections has recently been 320 millirems per injection, with a high of 800 millirems. Most of the exposure has been caused by the necessity for frequent entries into the cells for cleaning and direct repair of

Table 7. Measured exposure rates

Position	Injection 6 (mR/hr)	Operational injection 1 (mR/hr)
Over valve pit	32	164
Waste pump room	12	112
Well room window	4	12
Mixer cell side window	29	294
Cementer's station	6	110
HT-400 window	12	
HT-400 shield	5	17

in-cell equipment and cleanup operations after the injection. As in the case of the other hazards discussed, these exposures can be reduced by appropriate design changes.

Hazards Associated with the Underground Radioactive Grout

The objective of most radioactive waste disposal operations is to remove the radioactivity from the biosphere and store it in such a way that it cannot inadvertently reenter. Hydrofracturing is uniquely suited to this purpose. When accomplished properly and in a suitable geological formation, hydrofracturing fixes the waste permanently in the host rock in such a way that only deliberate mechanical operations or natural events of geological significance, which occur on epochal time scales, can cause it to be displaced.

After the waste has been mixed with the cement and other solids and injected deep underground into a fracture and after the mix has hardened, there is no apparent mechanism by which the radioactive materials might migrate back to the surface. The solids, certainly, are incapable of moving even if there should be a major earthquake accompanied by faulting, an event which would be quite without precedent in this part of the country. Fault displacements of 30 to 50 ft sometimes accompany major earthquakes in tectonically unstable areas (which eastern Tennessee is not), but with 700 ft of cover rock such displacements would be negligible.

There are no gaseous fission products present in the waste, except perhaps for trace amounts in solution. In the unlikely event that these should be released we know that the shale would be capable of retaining them, for it has retained small amounts of methane, nitrogen, and oxygen at pressures up to 30 psi during the 600 million years since it was deposited.

This leaves only water solutions as possible vehicles for the transport and dispersion of the radioactive materials contained in the grout. There are two possible sources of water: the water that was contained in the waste and groundwater which might make its way down from the surface and return back to the surface.

We know that the greater part of the water in the waste is fixed in the grout when it hardens, and we are working to improve the mix so that all of the water will be incorporated. This can be done in the laboratory, but it is not easy to duplicate the laboratory conditions in the field. A week or more after the waste has been injected and the cement has hardened, it will be our policy, as we have done occasionally in the past, to open the wellhead and bleed back any free water that may be present. Following operational injection 7 (ILW-7) the wellhead was opened, and some 8000 gal of mildly contaminated water was recovered. This may have come not only from ILW-7 but also from ILW-5 and ILW-6. These three injections totaled 280,000 gal of wastes, of which some 3000 to 4000 gal was wash water that was not mixed with solids. The disposal of wash water without solids into the fracture is a practice which we have minimized; it will be stored in the waste storage tanks and injected with solids at the start of the next operation. Under these circumstances, the recovery of only 8000 gal of water represents a good performance, and we believe it can be considerably improved. The three injections, through a misunderstanding that has since been corrected, were made with a mix consisting of only 5.5 lb of solids per gallon instead of the 6.0 lb called for. With the proper mix and better operating procedures, it should be possible to greatly reduce or even eliminate the volume of free water that separates out from the grout.

It is extremely difficult to imagine any realistic series of events which might make it possible for groundwater to descend from the surface down to the grout sheets, leach out the radioactive material, and then transport it back up to the surface. The 300 ft of cover rock, between depths of 400 and 700 ft, have been shown by several independent lines of evidence to be quite impermeable. As they are slowly arched up by repeated injections it is possible to imagine that some permeability will be induced in the shale as the result of this deformation. However, the bending amounts to a deflection of only a few inches at the center of a span some 4000 ft across, and this can be accommodated by the elastic and plastic deformation of the shale with no increase in its permeability. Also, the cover rock is being monitored to guard against any loss of its impermeability, so that no hazard on this score should be anticipated. Under all anticipated conditions, therefore, there will be no way for groundwater from the surface to get down to the grout sheets, much less move along these tightly filled fractures to pick up any of the contained radioactive materials and then move them back up to the surface.

The only credible hazards associated with the long-term presence of the waste material are those which arise because of the use of improper injection techniques or because of the selection of an unsuitable geological formation for the disposal site. In all cases of significance, hazards of the former kind can be detected and corrected. Elimination of hazards of the latter kind is accomplished by proper investigation of the formations to be penetrated and by adequate understanding of the physical characteristics required of formations suitable for hydrofracture.

In the case of the ORNL hydrofracture site, the area has been investigated extensively and is known to be well-suited for these operations.[10] The primary containment is provided by the several hundred feet of overlying essentially impermeable shale, which for some 600 million years has protected the underlying red shale into which the injections are made.

Although the primary containment is sufficient to isolate the grout sheets even in the very unlikely event that water should somehow breach this primary containment, a second barrier to the escape of radioactivity from the grout sheets would be the ion exchange capacity of the shale, the same capacity for containment that was demonstrated by the former waste pit system. Any natural pathway (if one could form) leading from the fractures to the surface would be itself in the nature of a fracture, and, as the shale cannot break cleanly normal to the bedding, the fracture would lead through broken or powdered shale. A natural fracture would expose any escaping liquid to a large surface area of shale with consequent decontamination by ion exchange.

A third line of containment is artificial and resides in the physical and chemical properties of the mix. Ideally, the mix should immobilize all the liquid in the waste and should incorporate all the activity either into the crystal structure of the newly formed minerals or should bind it up by ion exchange. In practice, there has been some phase separation. This can probably be reduced or eliminated by using a slightly higher proportion of solids.

Leaching. Several lines of evidence show that both the cover rock and the red shale into which the injections are made are impermeable. Examination of the rock cores recovered by drilling shows that the shale below about 200 ft is quite fresh and unweathered and that the rock is neither porous nor permeable. Pressure testing of the nine rock cover monitoring wells also shows the shale to be impermeable. Temperature measurements in the Joy well and in one of the wells drilled for the second fracturing experiment suggest that, while there may be some slow movement of groundwater to a depth of 200 ft, there can hardly be any movement below 400 ft. The red shale contains appreciable amounts of disseminated sodium chloride which would long since have been removed if the rock were subject to leaching. The red shale also contains small amounts of gas, roughly 95% nitrogen, 1% oxygen, and 4% methane under a pressure of 30 psi, which would not still be there if the red shale and the cover rock were at all permeable.

Despite repeated assertions of these facts, some readers of this report may profess to see in Fig. 2 a means by which groundwater might reach and leach the grout sheets. They may be influenced by the way in which the several formations, if followed up dip to the northwest, outcrop within a mile of the disposal site, thinking that water can move down these beds from the outcrop until it reaches the hardened grout sheets. But water cannot move through the shale below a depth of about 200 ft. The Rome sandstone is also equally impermeable, as in this area the sand grains of which it is composed are tightly cemented and the rock is more a quartzite than a sandstone. The so-called "three beds of limestone" which mark the boundary between the Pumpkin Valley shale and the gray shales of the Rutledge are limestone by convenience only. Actually, they are calcareous shale, like the rest of the Rutledge, but with a higher enough lime content so that they stand out in the gamma-ray logs, and they are not subject to solution by the groundwater. The grout sheets are well protected from groundwater movement by the shales into which they have been injected and by the adjacent impermeable formations.

In their natural state, therefore, the red shale and the cover rock (the gray shale) are quite capable of protecting the grout sheet from leaching. It is at present uncertain how much arching up and related deformation, due to the material injected, the cover rock can take without becoming at least slightly permeable. For each million gallons of grout injected, the land surface near the injection well is uplifted about 1 in. The 150 ft of red shale above our last grout sheet should be good for 15 more slots according to our present plans, and each slot should hold at least a half million gallons (four injections each of about 125,000 gal), so that the final total uplift should be less than 10 in. As the uplift extends out some 1800 ft from the injection well, the strain in the shale will be very small and can probably be taken up by elastic and plastic deformation of the shale. There is no reason to believe that the shale will fracture, but if it does the rock cover monitoring wells should give warning.

Fission product leaching. Despite the very low probability that groundwater can ever reach the grout, leaching studies indicate that even when the grout is finely ground, the ^{90}Sr-^{137}Cs leaching rates are extremely low. A series of experiments utilizing laboratory-hardened grout from experimental injection 5 showed that the ^{90}Sr-^{137}Cs leach rates decrease rapidly with time. From the data obtained, a leach rate which

10. W. de Laguna et al., *Engineering Development of Hydraulic Fracturing as a Method for Permanent Disposal of Radioactive Wastes.* ORNL-4259, Sec. 2 (1968).

decreases exponentially with exposure time can be inferred for the first few hundred hours. A total of 0.3% of the ^{90}Sr-^{137}Cs activity was leached from 60-mesh material after 500 hr. For grout hardened underground, the leach rate was about one-fifth of the laboratory-prepared material for a waste containing a mixture of ^{144}Ce, ^{137}Cs, and ^{90}Sr. For the waste used in experimental injection 4 which contained essentially only ^{137}Cs, the leach rate for grout hardened underground was $\frac{1}{40}$ of the laboratory-prepared material. Details of these experiments are given in ORNL-4259. Because of the reduction in surface area, the leach rate from a grout sheet $\frac{1}{4}$ in. thick would be expected to be about two orders of magnitude less than for the ground material. Even if water should gain access to the disposal formation, the grout sheet would not leach rapidly enough to be a hazard.

Plutonium leaching. During development of our waste-cement mix, the prime concern was retention of ^{137}Cs and ^{90}Sr in the grout; the question of ^{239}Pu was not even considered. Until operational injection 4, the ILW waste was not even analyzed for plutonium. Subsequently, however, concern was raised about the leachability of plutonium in the grout, and studies were undertaken to determine this with the current waste-cement mix.

An "order of magnitude" leachability was established using synthetic ILW waste and the solids blend now being used. Using a grout containing 0.18 μCi of ^{238}Pu per gram of solid grout and 2 ml of leaching water per gram of solid grout, the amount of ^{238}Pu leached after 24 hr of contact was 0.0024%. The area of the grout was 2.63 cm^2/g; thus, the initial leaching rate was 0.0009%/cm^2/day. Leaching rates, in general, decrease significantly with time; hence, one might consider this leaching rate to be representative of the highest rate.

To estimate the magnitude of leachability of grout in the disposal formation, the surface area of a grout sheet is required. Assuming the grout sheet is $\frac{1}{4}$ in. thick, then the area of a gallon of grout is 924 in.^{2}; the total leaching surface of a gallon of grout is 11,920 cm^2, considering both sides of the grout sheet. If the initial leach rate is 0.0009%/cm^2/day the activity leached would be 10.7% of all the activity in 1 gal of grout. In operational injection 7 the plutonium concentration was 1.7 Ci per 83,000 gal of waste (see Table 4). This amounts to 15.7 μCi per gallon of grout (the volume of grout is 1.3 $\times$ the volume of liquid waste). Thus, 1.68 μCi would be leached per gallon of grout in contact with 9060 ml of leaching water (consistent with the 2 ml of leaching water per gram of solid grout used in the laboratory test). The resultant concentration would be about 1.8×10^{-4} $\mu Ci/cm^3$. It should be remembered that these results are "laboratory" data; experience shows that the field grout is about 50 times more retentive, and thus the actual leaching rate would be proportionately less. Moreover, since leach rates decrease exponentially with time, such high leach rates would not persist over long periods of time.

Evidence that the actual plutonium leach rate is considerably lower than that indicated by this laboratory test is substantiated by the absence of plutonium in the bleedback from operational injection 7.

Thermal effects. The rise in underground temperature caused by the radioactive decay of injected waste depends upon the characteristics of the nuclides involved and their distribution underground. The maximum temperature, which will occur near the center of the region into which the waste material is injected, and for the class of mixtures under consideration (i.e., predominantly ^{137}Cs and ^{90}Sr), will be reached 40 to 50 years after injection. The exact time and temperature will depend upon the volume and thickness of the layer into which the radioactive material is injected, the time distribution of the injections, and their actual composition. In order to control the underground temperature, periodic calculations of the heat transfer situation will be made. These will be based upon the actual composition and configuration of the injected waste.

At present, it is estimated that the past injections, which included 350,000 Ci of ^{137}Cs and 26,500 Ci of ^{90}Sr and which are located in a region approximately three acres in area and 100 ft thick 800 ft underground, will cause a maximum temperature rise of approximately 1.14°F. This maximum will occur in about 49 years. The relatively small amounts of ^{106}Ru, ^{60}Co, and ^{239}Pu have a negligible effect in this calculation.

If a mixture of 90% ^{137}Cs and 10% ^{90}Sr is used as a reference material, the future storage of an additional 2.53×10^7 Ci in a region three acres in area and 200 ft thick would result in a maximum temperature rise of 70°F. This would take place over a period of about 48 years. Other mixtures of these and other nuclides will produce correspondingly different results.

No temperature-dependent mechanism is known which would be likely to cause significant changes in the Conasauga shale or the cement grout up to a temperature of as much as 200°F. The absence of a known mechanism is not in itself convincing; there are, however some positive indications that temperatures up to at least 140°F can be tolerated. Samples of shale from Salina, Kansas, that are relatively similar to the Conasauga shale have been tested at temperatures up to

200°C with no observed change in mineral structure. Also, the Conasauga shale at Oak Ridge has in the past been at appreciably higher temperature than at present. It has been established that at least 10,000 ft of formations have been eroded from the present site; if the current geothermal gradient is assumed, a shale temperature of at least 140°F can be calculated. Finally, cement grouts made from the type of cement used to date by the fracturing facility have been kept for considerable periods of time at 140°F with no change in grout strength and at 200°F with only a slight change in grout strength. It seems likely, therefore, that the Conasauga shale and grout could be heated to at least 140°F with impunity, and even higher temperatures may be found to be feasible when more information becomes available.

Another factor limiting the allowable temperature of the shale and grout formations is the thermal expansion of the shale. The temperature expansion of the Kansas shale was found to be 0.05% at 140°F. If a temperature of 140°F is assumed at a depth of 900 ft and a linear temperature profile is postulated, the overall vertical expansion will be 2.7 in. – 36% of the $7\frac{1}{2}$ in. of vertical expansion expected from grout injections. In fact, however, the temperature profile would not be linear and the overall expansion would be less, probably one-third or less of the value calculated above. Uplift of this magnitude is of little concern.

The calculations currently employed for the temperature distribution estimates utilize a one-dimensional model and conservative values of the physical parameters. Since no credit is taken for lateral heat transfer and since it is assumed that the cover rock has infinite rather than finite thickness, the estimates obtained are conservative.

It is estimated that during the next five or six years the underground heat inventory will increase to approximately 10.5 kW, which is equivalent to a maximum temperature rise of about 5.7°F.

Mechanical failures of the rock. Although not considered likely, the failure which appears to be of most concern is the possibility of the occurrence of a vertical rather than a horizontal fracture. A rather complete analysis of this problem is presented in ORNL-4259, Sect. 12, and it may be concluded that the probability of a vertical fracture is small and that it is possible to anticipate an increase in this probability by appropriate observations. Some 20 fractures have been made in the red shale at ORNL, and 2 fractures have been made in similar shale in New York State. All of these fractures have been horizontal, and it is evident that this is the normal mode of fracture in comparatively shallow well-bedded shale. Moreover, the formation of a vertical fracture would be indicated during the breakdown by pressure anomalies; hence, the injection would not be made. Finally, even should a vertical fracture occur during injection, there is, because of the configuration of the site, little probability that any hazard would result.

Other possible modes of rock failure are as follows:

Failure by a large increase in the permeability of the shale. The upward-directed displacements over and around the injection could cause an opening of joints and permeability channels in the shale, which might permit groundwater to percolate to the injection depth. The rock cover wells installed at the site were designed so that the permeability of the shale at the 550- to 650-ft-depth level could be measured periodically. This can be accomplished simply by measuring the rate at which water under relatively low but constant pressure flows into the strata. Any large increase in this acceptance rate following a group of injections would indicate that the permeability of the cover rock had been affected.

Failure of shear fracture along a conical surface. A sufficiently large number of nearly identically sized injections may be capable of inducing a shear stress in excess of the strength of the rocks so that an inverted cone-shaped mass of material would be "punched" up out of the ground. Stress analysis indicates that the shear stresses die out very rapidly upward and outward from the edge of the injection but that they are high near the tip. This would suggest that whereas such a failure may be initiated at the tip of the fracture it would not extend far enough to cause a failure.

Failure of the cement bonding a well casing into the hole. This type of failure would be localized at the site of the well, and any release would probably be small; it may be possible to repair the damage by suitable operations at the well. For these reasons, a failure of this type is not considered serious and probably would not force termination of operations.

Failure of casing at observation well. At several times the casing of various observation wells has been pulled apart by a grout injection. The occurrence is anticipated and guarded against by making sure that the valves on all observation wells are closed before an injection is begun.

Seismic effects. There remains to be considered a possible but unanticipated event which might let water into the grout, that is, a large earthquake. An earthquake by itself would have no effect on underground conditions; for important changes to take place there would also have to be faulting.

Faulting such as accompanies a truly major earthquake may involve vertical displacements as large as 30 to 50 ft. In hard brittle rock large faults of this type may shatter the rock along the fault plane and make a highly permeable pathway. In soft rock such as shale the rock along the fault is ground to powder, and the fault trace is impermeable. In drilling the Joy well, the trace of the Copper Creek thrust fault, which is some 230 million years old, was intersected at a depth of 1360 ft. The fault plane was represented by 2 to 3 ft of finely crushed shale, quite impermeable and showing by the lack of alteration or the deposition of any minerals such as calcite that no water had ever moved along it. Even an earthquake accompanied by faulting, therefore, would be quite incapable of forming a permeable channel down to the grout sheets.

Long-Term Containment. The cesium and strontium contained in the waste will remain a potential hazard for several hundred years. There are small quantities of plutonium and other transuranic nuclides in the waste which will remain, in ever decreasing amounts, for a much longer time, but by well less than a million years all the activity of all kinds will have decayed to harmless levels. We will consider here what might happen to release the radioactive materials in the grout sheets in a period of a million years. This consideration must be highly speculative for the only guide as to what may happen in this next million years is what has happened in the distant past.

The Appalachian Mountains, including the Valley and Ridge Province of which Oak Ridge is a part, were formed some 230 million years ago during the Appalachian Revolution. The rocks in the Valley and Ridge at this time are believed to have slid down from the slopes of the Appalachian Mountains proper along fault planes, such as the Copper Creek fault, in which friction was greatly reduced by fluid pressures. Following their first uplift, the mountain range, and presumably also the ridges which then represented the Valley and Ridge Province, were worn down to base level. This first period of erosion lasted a few million years and was followed early in the Triassic by a period of block faulting which formed trenches along the eastern margin of the Appalachians from Canada south to North Carolina. These trenches were filled with Triassic sediments and, following further uplift and faulting, were deeply eroded during the Jurassic.

During the Cretaceous continued slow uplift of the whole Appalachian area, an isostatic response to the earlier relief of load by erosion, was accompanied by continued erosion which reduced all or much of the region to base level. The magnitude of this erosion is evidenced by the thousands of feet of Cretaceous sediments which form the bulk of the deposits in the Atlantic Coastal Plain and in the Mississippi Embayment. This principal period of erosion was completed some 60 million years ago.

During the Cenozoic, and continuing down to the present, there has been a continuing very slow uplift and erosion of the area, marked by adjustments of the surface drainage. There was no mountain building, at least as this term is commonly employed, but the Appalachian Mountains and their associated foothills, including the ridges of the Valley and Ridge, were left higher than their surroundings due to their being composed of more resistant rock which was eroded away less rapidly. The amount of uplift and erosion during the 60 million years of the Cenozoic is uncertain, but to judge from the volume of sediments now resting in the coastal plains and in the embayment, it was much less than that which had occurred during the Mesozoic. In all, at least 10,000 ft of sediments were removed from the Oak Ridge area in some 230 million years. The rate of erosion at present is slow, much less than the average rate, and far less than 700 ft in a million years, so that if the present rate continues, as appears likely, the shallowest of our grout sheets will still be deeply covered by the time their radioconstituents have decayed to harmless levels.

During the past two million years, North America, as far south as Long Island and central Pennsylvania, was four times covered by continental ice sheets. These cut deeply into the earth in certain areas, forming, among other features, the Great Lakes. If the ice sheets should come as far south as Tennessee, they could lay open the grout sheets in our disposal area, but we believe that we are far south of the danger area. Further, if glaciers did come this far south the area would be uninhabitable, and the slow release of small quantities of radioactive materials would be of no consequence. Past history strongly indicates that natural processes will not uncover our grout sheets until long after their contained activity has decayed.

If natural processes will not uncover the grout sheets, is there any reasonable possibility that they will be brought to the surface by the activities of man? There is no deep-water-well drilling in the Conasauga shale, nor will there ever be, as the formation in depth is too impermeable to furnish water. It is conceivable, though unlikely, that there will be drilling for oil in this area at some time in the future. If there should be, such drilling will certainly be accompanied by detailed well logging, which would immediately reveal the presence of any radioactive materials. There are no known resources in the area worth deep mining, and, if there were, actual mining would be preceded by core drilling which also would immediately reveal the presence of any radioactive materials. Even granted our ignorance of what the million years will bring, it is very unlikely that the future activities of man will bring to the surface more than at most trace amounts of the radioactive materials disposed of at Oak Ridge by hydraulic fracturing.

CONCLUSIONS

The foregoing safety analysis indicates that the hydraulic fracturing facility as it exists at present in good repair is capable of disposing of ORNL's current ILW waste without danger of releasing significant quantities of radionuclides to the environment. No underground hazard is foreseen with continued operation of the existing facility (1) if the fractures continue to conform with the natural bedding (nearly horizontal), (2) if this fact is routinely verified by the monitoring of various observation wells, and (3) if the phase-separated water is routinely bled back through the injection well and reinjected later.

The safety analysis also shows several weaknesses in the existing surface plant that should be corrected as soon as possible. A number of improvements in the network of monitoring wells are indicated, and the radiation exposures received by the operators before, during, and after an injection should be reduced. These improvements should make the present facility adequate for the disposal of ORNL's current ILW waste for the next several years and allow it to handle even higher-activity wastes safely, if necessary (see Operating Limits, Appendix I). The various modifications are discussed in some detail below.

The radiation exposures of the operators of the hydraulic fracturing facility are received mostly during preinjection maintenance operations and postinjection cleanup. These exposures will be reduced by modifications to the Densometer system and slurry tub, by providing unit shielding for the injection pump and slurry tub, and by modifications to the high-pressure piping in the wellhead cell. In addition, improvements to the off-gas system will be made to reduce the airborne contamination.

The Densometer system will be modified to provide higher slurry velocity, easier access for maintenance, and better backwash facilities.

Postinjection cleanup of the existing slurry tub is complicated by the many angles and projections inside the tub. A new tub will be designed and built with smooth internal surfaces, a minimum of internal equipment, and better operating vision.

The Waste Storage Tank groundwater drain will be relocated.

Unit shielding for the injection pump will reduce the radiation exposures received during maintenance operations. Similar shielding on the roof of the mixer cell in the vicinity of the slurry tub will reduce the radiation exposures received during postinjection washup of this equipment.

Replacement of existing screwed fittings on the high-pressure valve rack in the wellhead cell with flanged fittings will permit replacement of individual fittings with minimum difficulty (and minimum radiation exposure). Replacement of the hand-operated valves with remotely operated valves will ease operations.

The off-gas system for the slurry tub will be enlarged and improved, and in addition, a new off-gas system will be provided for the waste pump house. Off-gases from the waste storage tanks will be connected to this system.

In addition to these improvements, at least one new gamma-ray logging well is needed for accurate location of the grout sheet after each injection.

The proposed modifications discussed above have been estimated at $152,000, exclusive of the logging wells. A logging well is estimated at $10,000 for the first well and approximately the same for each additional well.

In addition to the planned equipment modifications listed above several modifications to the operating procedures of the hydraulic fracturing facility will be made, and a set of operating limits will be adhered to (see Appendix I).

1. The compatibility of the waste solution and solids mix will be checked before each injection. Samples of the actual solids mix from each of the bulk storage tanks will be blended. The resulting grouts should have a phase separation of less than 5%, should not "flash set," should have an apparent viscosity of less than 20 P (measured on a Consistometer), and should set within 24 hr.
2. The ratio of solids mix to waste solution will be increased to at least 6.0 lb/gal.
3. A bleedback of free water will be made after each waste injection to reduce the free water associated with the grout and to provide data for mix evaluation.

Operating procedures are being updated. In particular, emergency procedures and check lists for operations of safety significance are being rewritten. These operating procedures will be issued as a separate document.

The modifications discussed above should make the hydraulic fracturing facility operable for the next several years with intermediate level waste of approximately the present composition. During this time, the experience gained with the modified facility and concurrent research and development work on sludge handling will determine the modifications required for a permanent facility.

This safety analysis shows that the hydraulic fracturing procedure is probably the safest and most effective method currently available for permanently removing radioactive waste from man's environment.

Appendix I

OPERATING LIMITS FOR THE SHALE FRACTURING FACILITY

ORNL's hydraulic fracturing facility was designed and built to handle intermediate-level waste solutions. For this reason, some of the limiting conditions on operations result from "above-ground" limits, while others are "below-ground" limits which are unique to the method of disposal. Based on the safety evaluation for the existing facility, the following limits apply to all operations.

A. Below-Ground or Geological Limits

1. **Temperature in formation.** The temperature rise in the disposal formation due to radioactive decay shall not exceed 70°F. Analysis of heat generation or transfer within the geological structure will be performed to demonstrate that the temperature limit is not exceeded. Such analyses will be performed every two years or after five injections, whichever occurs first.

   Basis. A temperature limit of 70°F has been established as a conservative level which will cause no significant change in the physical or chemical properties of the geological structure. The parameters listed below will be controlled during the operation. Although the following parameters are controlled during the operation, operating limits on each are not suggested since individual parameters can be varied over a wide range by making compensating changes in the remaining parameters.

   a. Fission product activity of waste (thermal energy and decay characteristics).
   b. Quantity of waste injected in each slot.
   c. Spacing of waste injections.
   d. Total volume of waste injected.

   As an example consider: 60 injections involving ^{137}Cs, 4 injections per sheet, 140,000 gal per injection, and 13 ft between sheets would limit the average fission product content to about 3.4 Ci/gal. Smaller volumes of higher-activity waste could also be injected; for example, in the above scheme if one injection of 140,000 gal per sheet were substituted for each of the injections totaling 560,000 gal, then the concentration could be increased from 3.4 to 13.6 Ci/gal.

2. **Transuranic activity.** The transuranic activity of the waste solution shall be limited to an average of 2×10^{-3} Ci/gal.

   Basis. If the waste concentration is limited to 2×10^{-3} Ci/gal, the concentration in the grout-shale combination will be limited to a concentration of 10 μCi/kg. This concentration of transuranics is below the concentration considered acceptable for this type of disposal. Hydrofracture provides assured storage underground for many millions of years; however, after a period of only 250,000 years, the alpha activity in the rock would be reduced by a factor of at least 1000, producing a concentration less than 10 nCi/kg.

3. **Injection locations.** Injections of waste are limited to the existing waste injection area and to injection within the Pumpkin Valley member of the Conasauga shale.

   Basis. Injections of waste are limited to locations where the geological structure has been thoroughly examined. Adherence to this limitation assures that wastes are injected into an acceptable formation.

4. **Monitoring requirements**

   a. **Test wells.** Rock cover leak test wells shall be maintained in operable condition and shall be examined every two years or after five injections (whichever occurs first) to determine the cover rock's acceptance of liquid at a pressure of 75 psig. If the acceptance rate is greater than 10 gal/hr, operations are to be halted until further checks can be made on the permeability of the overlying rock.

   Basis. The containment integrity of this method of waste disposal depends upon maintaining low permeability in the rock structure. These tests provide periodic checks of the effects of the operation on the permeability of the rock structure.

   b. **Bench marks.** Bench marks shall be maintained at a representative number of locations at the site, and an accurate record shall be established every four years or after ten injections (whichever occurs first) to determine the nature and extent to which surface topography has changed. If there are indications of stepwise changes in the topography or other unexplained changes in topography, operations are not to be resumed until it has been established that injections have not caused vertical fractures or have damaged the cover rock.

Basis. Periodic examination of bench marks provides an indication of the effects of the injections on the overlying rock structure. Any step changes in topography may be indicative of vertical fracture or breaking and faulting of the cover rock. Individual injections cause such small changes in topography that a check after ten injections is considered adequate.

B. Limits Prior to Injection

1. **Waste solution.** Prior to transfer of waste to the site, a sample of the waste solution shall be analyzed to assure compliance with the following limitations:

   a. **Radiochemical analysis.** A radiochemical analysis of the waste solution will be made to determine the radionuclide content.

   b. **pH.** The pH of the waste solution prior to mixing shall be no less than 4.

   c. **Transuranic activity.** The transuranic activity of the waste solution shall be limited to 5×10^{-3} Ci/gal.

   d. **Beta-gamma activity.** The beta-gamma activity of the waste solution will be limited to a maximum of 2 Ci/gal.

   Basis

   a. Information regarding the radioactivity type and amount is needed to assure compliance with limits A.1 and B.1.c and B.1.d.

   b. The pH level is maintained at 4 or greater to prevent excessive chemical interaction between waste solution and grout mix.

   c. The transuranics are limited to a level of 5×10^{-3} Ci/gal to assure that the release of transuranics from the ventilation system will not allow occupational or annual average environmental concentration guides (as appropriate) to be exceeded.

   d. This level of beta-gamma activity is established consistent with shielding design and experience with maintenance activities during postoperations.

   (Note that limits 1.c and 1.d relate to above-ground health physics considerations rather than to the underground limits of part A.)

2. **Waste-cement mix.** Based on the characteristics of the waste solution, a waste-cement mix shall meet the following requirements:

   a. **Consistency.** The consistency of the grout mix should be no greater than 20 P after pumping at a pressure of 2000 psi and a temperature of 70°F for 10 hr.

   b. **Setting time.** The setting time of the grout mix should be no greater than 24 hr.

   c. **Compressive strength.** The compressive strength of the hardened grout should be no less than 100 psi.

   Basis. Experience has shown that waste-cement mixes meeting these requirements can be handled safely and meet containment requirements.

3. **Equipment.** The following equipment must be operable before a waste injection operation is initiated.

   a. **Mechanical**

      1. One injection pump for pumping waste-cement mix.
      2. One spare injection pump for pumping water.
      3. One waste pump for pumping liquid waste.
      4. One TBP pump.
      5. One air compressor for operation of solids transfer equipment.

   b. **Instrumentation**

      1. One well pressure indicator.
      2. One waste tank level indicator for each feed tank.
      3. Either one solids flowmeter or one density meter for measuring the density of the waste-cement mix.

   c. **Filtration equipment.** The tank off-gas filters shall be tested during checkout prior to each injection.

   d. **Pressure relief valve.** The 7500-psig pressure relief valve on the waste injection pump will be tested during checkout prior to each injection.

   Basis

   a. This equipment is necessary in order to permit the injection to proceed. The only safety-oriented equipment is the gasoline- or diesel-driven injection pump and its spare, one of which is needed to flush and clean up the well in the event that the injection must be terminated.

b. This equipment is necessary in order to satisfy the requirements of safety limits C.1 and 2.

c. This is to ensure that the filters are adequate to remove 99.97% of the particles of greater than 0.3 μ diameter and thus fulfill the requirements implied by E.3.

d. This is to ensure that the equipment is in proper operating condition.

C. Limits During Injection

1. **Pump and well pressure.** The pump and well pressure shall be no less than the overburden pressure and no more than 7500 psig.

   Basis. A pressure less than the overburden pressure may indicate a malfunction. Pressure is limited to 7500 psig to keep within the design pressure of the equipment.

2. **Waste tank levels.** The feed tanks' levels shall be no less than 5% full.

   Basis. This is to prevent inadvertently running a feed tank empty.

3. **Water**

   a. There shall be a minimum of 500 gal of water available for the spare injection pump.

   b. There should be a minimum of 1500 gal of water in the process water storage tank.

   Basis. This amount of water is sufficient for flushing and cleanup should it be necessary to terminate the injection.

4. **Emergency waste trench.** The emergency waste trench shall be capable of receiving the total amount of waste injected during a given operation.

   Basis. In the event of particular failures, this trench is provided to collect any waste discharged from the well. The trench must have a capability to receive all of the waste injected in a given operation.

D. Limits Following an Injection

1. Bleedback. Not less than one week following completion of the injection, but prior to the next injection, the well will be reopened, and the phase-separated water will be bled back to the suitable storage facilities.

   Basis. Bleedback minimizes the amount of water contained in the formation and also provides a check on the adequacy of the waste-cement mix.

2. **Special investigations.** Normal monitoring requirements established in A.4 shall be supplemented by special investigations if there is indication during the injection that there may have been a malfunction.

   Basis. During the operation, pressure monitoring provides information to indicate if there has been a malfunction of the well. If such is indicated, special investigations shall be implemented to determine the type and extent of the malfunction.

E. Administrative Controls

1. **Organization.** The following minimum operating staff is required for operations. All personnel shall be adequately trained for their respective positions.

   a. ORNL

      1. Supervisor. One supervisor is required and has overall responsibility for the injection.
      2. Operator. One chemical operator is required to control the valving of the waste storage tanks and TBP addition during injection.
      3. Health physicist. One health physicist is required during the operation.

   b. Service company

      1. Supervisor. One supervisor is required.
      2. Operator. Two cementing operators and one equipment operator are required during the injection.
      3. Mechanic. One mechanic is required for equipment repair and mechanical adjustments as needed.

   Basis. A minimum number of qualified personnel are required to operate the facility and to take actions during emergencies.

2. **Procedures.** All operations shall be in accordance with documented operating procedures. Such procedures shall include a description of the startup, operation, and shutdown of the facility as well as the emergency actions to take for foreseen accidents. The procedures shall include not only the normal and abnormal operating procedures, but those procedures established for changing the design or mode of operation.

   Basis. Operation of the facility within established operating procedures minimizes the probability of an unsafe operation. Procedures provide the basic link between the designer and the operator.

3. **Radiation limits.** All operations are to be planned and executed such that the radiation limits under normal conditions do not exceed the following:

a. The whole-body or gonadal dose will not exceed 1 rem per injection.

b. The cumulative total dose is within guidelines established in MC 0524.

Basis. Operations within these limits will not cause an undue hazard to the general public or to the employees.

Appendix II

ADDITIONAL PLANT MODIFICATIONS CONSIDERED

Several additional modifications to the hydraulic fracturing facility have been considered but are not included in the items listed previously because the hazard or operating problem did not seem to be a major one. These modifications included alternate slotting techniques, relocation or replacement of the mass flowmeter, and additional wellhead safety devices.

The periodical cutting of a new slot in the injection well casing will remain a source of contamination. The use of explosive cutting devices is a possibility, but this method has serious drawbacks, notably an uncertainty as to the effect of ragged holes in the casing or a partially severed casing on the orientation of the fracture formed in the bedded shale. Casing slotting will be a relatively rare operation (every 4th injection), and its contribution to contamination problems at the surface is probably low enough to be tolerable. For this reason, the development of an alternate slotting technique is probably unnecessary. A careful determination of the spread of contamination that actually occurs during the slotting operation is needed, however.

The mass flowmeter required frequent maintenance and is presently located in an appreciable radiation field. This instrument should be relocated in a more accessible location or replaced with some alternate device for measuring solids flow. It is not obvious at the present time how either approach could best be done. Some development work is required on this problem before any change can be recommended.

A careful evaluation of the long-term safety of the injection wellhead fittings is needed. Well shutoff devices are available, but it is not clear that wellhead safety would actually be increased by their use. A pipe ram could sever the injection tube so that it would drop to the bottom of the well, and a valve below the pipe ram would then close off the well. These devices would provide backup protection for shutoff valves on the tubing string and annulus, but a leak in or below the protective fittings would remain a possibility, however remote. A storm choke (special ball check valve) could be installed below ground level, but it could not be used with a central tubing string, and its continued successful function in a cement grout environment is open to serious doubt. The best approach would seem to be a periodic inspection of the wellhead components and a periodic replacement of those fittings most subject to fatigue.

SUMMARY

This safety analysis indicates that the hydraulic fracturing facility as it exists, in good repair, is capable of disposing of current ILW waste solutions without danger of releasing significant quantities of radionuclides to the environment. No hazard is foreseen for continued operation of the facility if the horizontal nature of the fractures is routinely verified by the monitoring of the various observation wells and if the phase-separated water is routinely bled back through the injection well for subsequent reinjection with the next injection.

The hydraulic fracturing plant is situated about a mile from ORNL. The site was chosen because the subsurface geology was known to a depth of 3200 ft, because a waste transfer line from the Laboratory was nearby, and because the site was remote enough from the Laboratory so that any release of radioactive waste solution that might occur would be much less serious than a similar leak in the Laboratory area.

There are underground shale formations at the site that are believed to be suitable for waste disposal injections at several depths – 692 to 1002 ft, 1642 to 1847 ft, and 2650 to 2850 ft. These formations are well below the deepest known water-bearing formations (about 200 ft). For the series of experimental injections that was contemplated, it was necessary to plan for the recovery of a number of cores of the injected grout sheets. For this reason, the shale formation between 692 and 1002 ft was chosen for the experimental injections.

The shale formation into which all waste injections have been made is the Pumpkin Valley member of the Conasauga shale. It is a dense argillaceous shale that is very thin-bedded and dominantly red. It is overlain by a gray calcareous shale interbedded with generally thin beds or lenses of limestone. Very locally there is some movement of groundwater in this upper shale to depths of 100 to 200 ft, but the amount of water reaching these depths is very small. There is no known movement of groundwater below 200 ft. The Pumpkin Valley shale contains appreciable amounts of dispersed sodium chloride and small amounts of trapped gases (mainly methane and nitrogen) – evidence that this formation is well isolated from the surface or near-surface environment. Oak Ridge is located in an area of moderate earthquake frequency but of small earthquake intensity. There is no record or evidence of any faulting in this area associated with earthquakes.

Prior to 1965 the intermediate-level liquid waste produced at ORNL was disposed of by pumping it into shallow seepage pits excavated in the surface shale. The ion exchange properties of the weathered shale retained the radionuclides and permitted the bulk of the liquid waste to seep through. In 1965–1966 the Laboratory constructed a waste evaporator for the concentration of this intermediate-level waste. Starting in 1966 the use of seepage pits was discontinued, and the concentrated waste solution has since been routinely injected by the hydraulic fracturing plant. To date over 600,000 gal of waste containing almost 400,000 Ci have been mixed with cement and other additives and injected into the Conasauga shale. The waste has averaged less than 1 Ci/gal of beta or gamma emitters and is about 90% ^{137}Cs and 10% ^{90}Sr. The concentration of transuranics in the waste solution has been about 2×10^{-5} Ci/gal, about 60% ^{244}Cm and 40% plutonium. This concentration of transuranics is less than half the AEC limit (10 μCi/kg) for surface burial of a contaminated material.

The equipment used for the injection of each batch of waste consists of a waste transfer pump and spare, four bulk storage tanks to store the cement and other solid constituents of the mix, a surge tank, a high-pressure injection pump, a standby injection pump and mixer, and assorted valving and special equipment. The mixer, surge tank, injection pump, and wellhead valving are installed in cells to reduce the radiation exposure of the operators and limit the area that would become contaminated in the event of a leak in the equipment or piping.

A total of seven experimental injections and seven operational injections have been made at the hydraulic fracturing plant. Very few operational difficulties have been experienced. The average exposure of the operators has been 320 millirems for the operational injections; most of this exposure has resulted from repairs of in-cell equipment and cleanup operations.

Monitoring of the gamma-ray logging wells has shown that the fractures and grout sheets formed during the various injections have followed the bedding. The record of injection pressures and data from the rock cover monitoring wells and bench mark leveling have tended to substantiate this conclusion.

The operational injections were in general made with a solids to waste ratio that subsequent experience has indicated was too low. As a consequence, the grout has failed to retain all of the associated water and a layer of free water has formed above the grout sheets. Available data indicate that less than 5% of the injected waste volume remains as free water and that this free water contains about 0.1% of the injected beta and gamma emitters and no plutonium. Most of this free water has been "bled back."

The safety analysis of this operation was based upon the configuration of the fracturing plant as it presently

exists. Three categories of hazards were considered: preinjection hazards, injection hazards, and underground hazards. The preinjection hazards were not unique to the hydraulic fracturing operating. The only injection hazard that was considered serious is the rather remote possibility of an injection wellhead rupture. The most serious underground hazard is considered to be that of the free water formed when the injection slurry does not contain a high enough proportion of solids. Since some future migration of this water is conceivable, this hazard will be reduced by the use of a higher proportion of solids in future injections and by a routine "bleedback" of any free water through the injection well to the waste-storage tanks for reinjection at a later date. Thermal effects of the waste, mechanical failure of the overlying rock, and seismic effects are not considered to be serious.

Several modifications to the existing facility will be made prior to the next injection. These modifications will improve the network of monitoring wells and reduce the radiation exposure received by the operators before, during, and after an injection. In addition to these planned equipment modifications several modifications to the operating procedures of the hydraulic fracturing facility have been made, and operating limits have been established. These improvements should reduce even further the hazard of operating the present facility and make this facility adequate for disposal of ILW waste for the next several years.

Procedures are being rewritten covering the entire operation. In particular, emergency procedures and check lists for operations of safety significance are being written. These operating procedures will be issued at a later date as a separate document.

The modifications that are discussed above should make the hydraulic fracturing facility operable for the next several years with intermediate level waste of approximately 2 Ci/gal of beta and gamma activity and up to 2×10^{-3} Ci/gal of transuranic activity. During this time the experience gained with the modified facility and concurrent research and development work on sludge handling will determine the modifications required for handling and disposing of more active liquid wastes and sludges.

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SAFETY ANALYSIS OF WASTE DISPOSAL BY HYDRAULIC FRACTURING AT OAK RIDGE

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